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TITLE
INVESTIGATION INTO THE PHYSICS OF SHIP CAPSIZING BY COMBINED CAPTIVE AND FREE-RUNNING MODEL TESTS

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SUMMARY: A comprehensive study of the physics of capsize phenomenon, focused on the behavior of small fishing boats in extreme waves, has been conducted by the National Research Council of Canada. The paper presents a philosophy of an original concept of experimental investigation into the mechanism of ship capsizing, which consists in a specially designed composition of free and captive model tests. Also outlined are the experimental technique developed and the test program.

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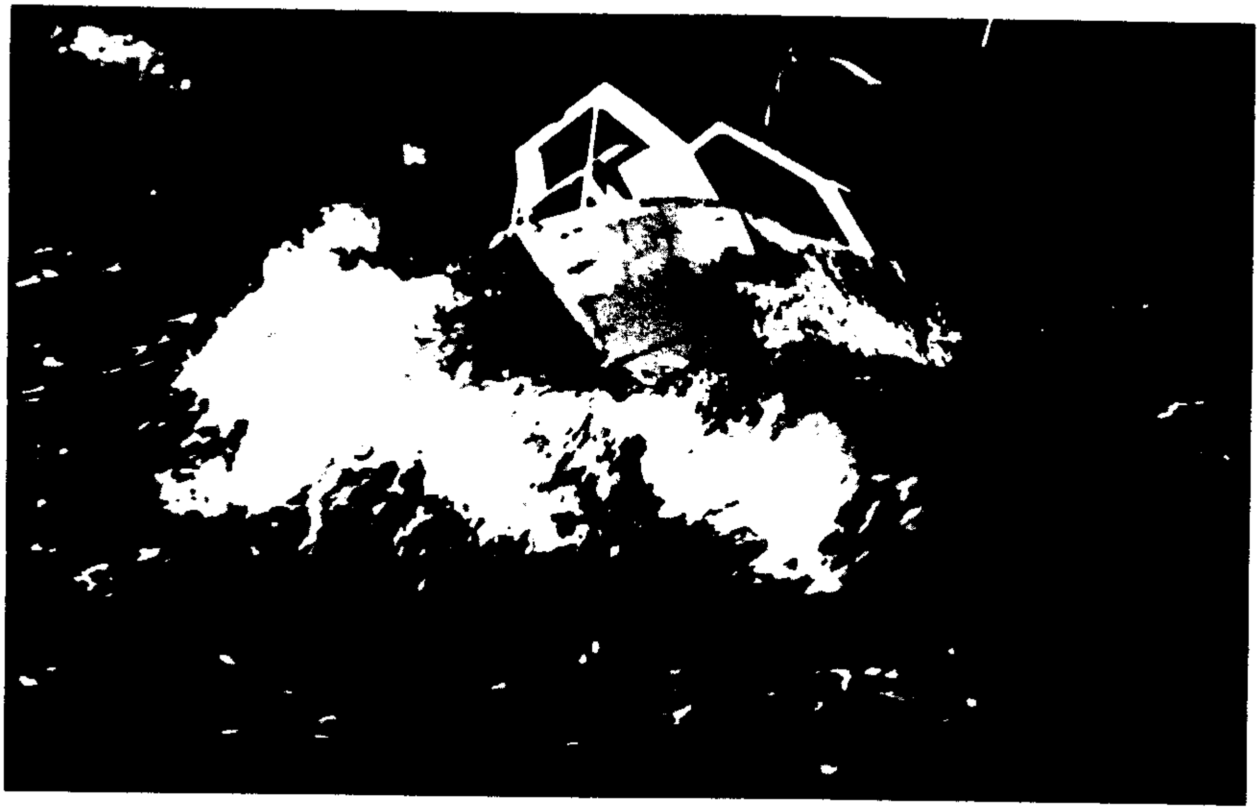

Model of a fishing vessel running in breaking quartering waves

Investigation into the Physics of Ship Capsizing by Combined Captive and Free-Running Model Tests

Stefan Grochowalski,[1] Member

Ship capsizing in heavy seas is a problem which still awaits a solution. A comprehensive study of the physics of capsize phenomenon, focused on the behavior of small fishing boats in extreme waves, has been conducted by the National Research Council of Canada. The paper presents a philosophy of an original concept of experimental investigation into the mechanism of ship capsizing, which consists in a specially designed composition of free and captive model tests. Also outlined are the experimental technique developed and the test program. The obtained experimental data are unique. The presented detailed analysis of some of the free model runs gives an insight of ship kinematics in quartering and beam waves, while the examination of the captive tests identifies the composition of the exciting hydrodynamic forces and moments. The majority of the paper is dedicated to analysis of the mechanism of ship capsizing in quartering waves. Various types of capsize and their causes are presented. Special attention is paid to the influence of bulwark submergence. The hydrodynamic phenomenon and the subsequent couplings and heeling moments created by bulwark submergence are discussed. Some other factors influencing ship capsizing are also considered.

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1. Introduction

THE SOLUTION of the ship capsizing problem is one of the major challenges that scientists and naval architects have to meet. The problem is as old as shipbuilding itself. It concerns ship operators and designers and has preoccupied researchers' attention for many years. Capsize disasters are so painful, not only because of material losses, but primarily because they take human lives.

It is not strange, therefore, that the matter is raised and discussed so frequently. It is amazing, however, how little progress is being made despite the considerable amount of research that has been carried out in this field worldwide.

At present, there is no scientifically based stability safety criterion, and there is no mathematical model of ship capsizing in the general case of operation in extreme waves.

The complex physical nature of the capsize phenomenon and the large number of possible scenarios are the main reasons for this situation. This is reflected in the work of the International Maritime Organization (IMO), where various stability standards and criteria have been proposed and discussed for many years, and yet some classes of vessels are not covered by safety standards, while the implemented criteria are considered to be very unsatisfactory. They are in practical use because of lack of criteria that are more adequate.

Two predominant approaches to the ship capsizing problem can be observed at present. One of them is based on the classic assessment of stability safety by analysis of the righting moment curve in comparison with external, usually stipulated, heeling moments. The major efforts are focused either on establishing requirements for the shape and values of the *GZ* curve (calculated in calm water or on a wave crest) so that a required safety level can be maintained during ship operations in unspecified sea conditions, or on establishing the nominal heeling moments which the ship has to withstand (statically or dynamically or both).

The required safety standards are usually a result of a detailed stability analysis of a particular type of ship or some statistical studies of safe ships and casualties, and reflect so-called "good marine practice." They may provide a reasonable safety level for some classes of ships or some operational situations but in other cases they are not satisfactory or fail completely.

The second trend represents efforts to base the stability criteria on more sound theoretical models. However, the studies are focused on some selected simplified cases which are related to ship behavior either in beam or following seas. Although the selected situations are realistic, they do not represent the most severe scenarios of ship operation in oblique extreme seas, and none of the proposed approaches is general enough to represent the whole range of phenomena affecting ship stability.

An example of a stability study which avoided this weakness is the Hamburg Ship Model Basin's (HSVA) comprehensive model testing of ship behavior in quartering waves [2,3].[2] However, the applied experimental technique and the method of analysis of the results do not allow adoption of the developed stability criteria to classes of ships other than that class for which the tests were carried out, that is, fast containerships.

It will be very difficult (if not impossible) to generalize the results of studies of particular simplified cases, while the rationality of improvements of traditional methods, based on "sufficient" righting arms curve, can always be questioned. The situation is particularly difficult in the case of small fishing vessels. The variety of hull forms, loading conditions (changing during operations at sea), operational and environmental circumstances, make the safety assessments extremely difficult.

The lack of applicable stability criteria and frequent capsize disasters involving small fishing vessels prompted the Canadian Coast Guard a few years ago to request the Institute for Marine Dynamics of the National Research Council of Canada to formulate and undertake a corresponding research program [4].

It was agreed that, in order to avoid the weaknesses of existing stability criteria, and to lay out a sound scientific base for future regulations, a fundamental study of the capsizing phenomenon must be undertaken.

The primary objectives in the first stage of the project were defined as:

1. investigation of the physics of the capsize phenomenon in the general case,
2. development of a numerical code for time-domain simulations of motions and capsizing of an arbitrary ship in extreme waves with random headings; and
3. formulation of a mathematical model of ship capsizing in severe seas.

The deterministic approach seemed to be the most appropriate at this phase. It should provide a basis for further study of the influence of ship design parameters on a vessel's propensity to capsize in various selected critical conditions.

Following some preliminary analyses and a review of results of various model tests,the instance of a ship moving in quartering, breaking waves was selected as the subject of the study. It was concluded that this is the most severe and also the most general case in which all potentially dangerous situations, usually investigated separately, may be present in a single event. Furthermore, capsizing in quartering waves may also occur as a totally transient event due to some factors usually not considered in the equations of roll.

In studies of such a complicated dynamic phenomenon it is essential to detect all the major factors and elements which play a decisive role. Obviously, this cannot yet be done by theoretical considerations alone. Appropriately designed and scrupulously performed physical model experiments can be the most valuable source of otherwise unobtainable information and can form an excellent basis for the validation or calibration of numerical simulation programs.

For these reasons a special experimental program was designed. The objective was not to examine systematically the stability of a certain vessel or class of vessels in various environmental conditions, but rather to investigate the physics of the capsize phenomenon in general and the most critical situations.

The model tests were carried out at the SSPA Maritime Consulting facilities at Göteborg, Sweden in 1984–85. In parallel with the analysis of the experimental results, the development of a computer time domain simulation program for ship motions and capsizing in extreme waves was continued. The first version of the computer code and some comparisons of the calculated and experiment results are presented in [5]. The results of the model tests are still being carefully analyzed.

This paper presents the concept and philosophy leading to the design of the performed set of free and captive

[2] Numbers in brackets designate References at end of paper.

model experiments, and outlines the experimental technique developed and the test program performed. Detailed analysis of some of the free model runs gives an insight of ship kinematics in quartering and beam waves, while the examination of the captive model tests identifies components of exciting hydrodynamic force and moment.

The major part of the paper is dedicated to the analysis of the mechanism of capsizing in quartering waves. Various types of capsize and their major causes are presented, with particular emphasis on the influence of bulwark submergence. Some other factors which have an influence on ship capsizing are discussed as well. The results prove that the experimental approach is very useful and provides a unique opportunity to gain a better understanding of the mechanism of ship capsizing.

2. Philosophy of the experimental approach

The dynamic identification of a ship from the capsizing point of view could be completed if for any set of environmental conditions two components of the phenomenon:

- composition of externally exerted forces and moments, and
- corresponding response of a ship, are fully identified.

As the hydrodynamic forces are caused by the surrounding environment, we deal with a chain of intermediate physical phenomena which together constitute a "cause-result" chain. The key elements of this chain are presented in Fig. 1. All of these elements and the strict quantitative relations between them must be completely identified if a mathematical model of ship behavior is to be developed, or the validation of a numerical simulation carried out. Because of the large number of factors which play a role in ship behavior in extreme waves, a simple analysis, and comparisons of the cause (waves) and response (ship motion) only are not sufficient.

However, the problem lies in the fact that it is impossible to measure the exciting hydrodynamic forces and the model response at once. Therefore, the usual practice in the experimental investigation of ship capsizing is the measuring of the behavior of a free model in various wave

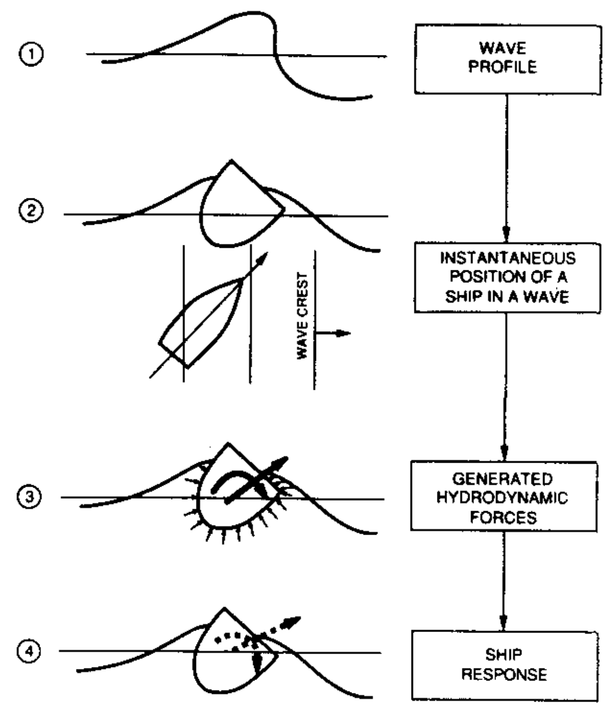


Fig. 1 Elements of the "cause-result" chain in ship motions

configurations. These types of tests may be very useful for the stability estimation of a particular ship in specified environmental conditions, but they do not give any information about either exciting forces or the force-response relationship during complicated motion and capsizing. Obviously, the identification methods based on linear theory, which are used in seakeeping, are not applicable to this case.

A special composition of experiments was designed to solve this complex problem. The principles of the idea could be summarized as follows:

(*a*) The dynamics of large-amplitude motions and capsizing in specified waves, loading and propulsion-steering

Nomenclature

- A_ϕ = hydrodynamic added mass moment in roll
- F_x, F_y, F_z = hydrodynamic force in surge, sway, and heave, respectively
- GM = initial metacentric height
- H = wave height
- J_{xx} = mass moment of inertia upon G-X axis
- k_{xx}, k_{yy}, k_{zz} = radius of gyration in roll, pitch, and yaw, respectively
- LCG = longitudinal center of gravity
- M_x, M_y, M_z = hydrodynamic moment in roll, pitch, and yaw, respectively
- M_B = buoyant part of wave exciting moment
- M_D = difractional part of wave exciting moment
- M_E = total wave exciting moment
- M_{FK} = total Froude-Krylov moment
- M_I = inertial part of wave exciting moment
- M_N = damping part of wave exciting moment
- M_S = inertial part of scattering moment
- M_{SD} = total scattering moment
- M_ϕ = hydrostatic restoring moment
- δM_x = additional roll moment created by bulwark submergence
- δM_{XS} = additional heeling moment due to lateral motion while bulwark is submerged
- δM_{XH} = additional heeling moment due to heave while bulwark is submerged
- N_S = damping part of scattering moment
- N_ϕ = hydrodynamic damping in roll
- R = hydrodynamic reaction
- S = instantaneous shape of immersed part of hull in a wave
- T = wave trough, wave period
- T_M = modal period of irregular waves
- t = time
- v = forward speed
- γ = spectrum parameter of irregular waves
- δ = rudder angle
- Θ = pitch angle
- μ = course (heading) angle
- ϕ = roll angle
- Φ_w = radiation velocity potential
- Φ_s = scattering potential
- Φ_ζ = undisturbed wave velocity potential
- ψ = yaw angle

conditions will be simulated by use of the free-running model technique.

(*b*) The hydrodynamic forces, generated on the ship by the same specified waves, and at the same conditions as for a free-running model, can be measured on a model restrained at a specified "frozen" position, moving with the same forward speed. The corresponding experiments are named "captive model tests."

(*c*) In order to reconstruct the capsizing mechanism, the free-running and the captive model tests must be correlated so that for every instantaneous position of the model with respect to the wave profile in the free-running situation, the appropriate "frozen" situation in the captive tests can be found, and the composition of the hydrodynamic forces interpolated. This can be achieved if in both cases the wave profiles and forward speeds are the same and the range of headings and heel angles in the captive tests cover the range of changes of those parameters in the free-running tests.

The traditional description of ship motions in wave splits the total hydrodynamic force into separate parts which reflect the physics of the involved phenomena. In a general case, the equation of a motion contains the following categories of forces:

$$\begin{matrix}\text{Inertial}\\\text{force}\end{matrix} + \begin{matrix}\text{Damping}\\\text{force}\end{matrix} + \begin{matrix}\text{Restoring}\\\text{force}\end{matrix} + \begin{matrix}\text{Wave exciting}\\\text{force}\end{matrix} = 0$$

As the physics of the forces generated on a body by waves is the same as the nature of the hydrodynamic forces of the body motion on calm water [6–8], the wave exciting force can be divided into the following components:

$$\begin{matrix}\text{Wave exciting}\\\text{force}\end{matrix} = \begin{matrix}\text{Buoyant}\\\text{force}\end{matrix} + \underbrace{\begin{matrix}\text{Wave diffraction}\\\text{force}\end{matrix}}_{\begin{matrix}\text{Inertial part}\\\text{of diffraction}\end{matrix}\quad\begin{matrix}\text{Damping part}\\\text{of diffraction}\end{matrix}}$$

In the case of roll motion, the equation could be presented in the form:

$$[I_{xx} + A_\phi(S,\Phi_u)]\ddot{\phi} + N_\phi(S,\Phi_u,\dot{\phi}) + M_\phi(S,\phi) = M_E(S,\Phi_\zeta,t) \quad (1)$$

where the wave exciting moment

$$M_E(S,\Phi_\zeta,t) = M_B(S,\Phi_\zeta,t) + \underbrace{M_I(S,\Phi_\zeta,t) + M_N(S,\Phi_\zeta,t)}_{M_D(S,\Phi_\zeta,t)} \quad (2)$$

The structure of equation (1) is based on the superposition principle, assuming that the components of the total hydrodynamic force during ship motions in waves can be considered as a sum of the forces generated by an oscillating ship in calm water (radiation and hydrostatic forces) and forces generated by the waves on a restrained hull (Froude-Krylov and diffraction forces).

This can be considered to be valid only in some applications to the analysis of seakeeping, where the amplitudes of motions are limited to certain values.

In the case of ship motions in extreme waves and capsizing, this principle is not valid. There is a strong continuous interference of the fluid flow caused by ship motions with the flow generated by the presence of the ship in progressive waves and the radiation and diffraction effects cannot be distinguished. The correct form of this equation should be

$$I_{xx}\ddot{\phi} = [M_B(S,\Phi_S,t) - M_\phi(S,\Phi_S,t)] + [M_I(S,\Phi_S,t) - A_\phi(S,\Phi_S,t)\ddot{\phi}] + [M_N(S,\phi_S,t) - N_\phi(S,\Phi_S,t)] \quad (3)$$

or, shortly:

$$I_{xx}\ddot{\phi} = M_{F-K}(S,\Phi_S,t) + M_S(S,\Phi_S,t) + N_S(S,\Phi_S,t) \quad (4)$$

where M_{F-K} denotes buoyant (Froude-Krylov) moment, while M_S and N_S denote the inertial part and damping part of the scattering effects, respectively. Each component of the total hydrodynamic moment in (4) is a function of the instantaneous shape of the immersed part of the hull in a wave and of the kinematics of the body motion relative to the wave flow. These two factors are represented by the second element in the causal chain (Fig. 1).

The experiments with a free-running model should allow the identification of elements 1, 2, and 4 (Fig. 1), where the measured motions result from the total hydrodynamic force and moment represented by the right-hand side of equation (4).

The tests with a fully restrained model which moves with required forward speed, heading and fixed angle of heel (fully captive tests), provide a possibility to measure the total hydrodynamic force and moment generated by the waves on the model at a particular "frozen" position. This force and moment, however, are not the same as those represented by equation (4). The restraints in the motion eliminate its influence on the generated velocity and pressure fields. This means that components $A_\phi(S,\Phi_S,t)\ddot{\phi}$ and $N_\phi(S,\Phi_S,t)$ in equation (3), which represent added mass and damping in calm water, are eliminated.

Thanks to the fact that the conditions are well specified, fully captive model tests are the most convenient for a validation of theoretically developed computer programs and for analyses of the influence of various factors (such as forward speed, drift, heading angle, hull shape) on the generated wave exciting forces.

In the studies of ship capsizing, however, the full constraint applied to the body makes the hydrodynamic phenomenon too different from the one in the unrestrained condition. In particular, the elimination of the buoyancy self-adjustment mechanism causes significant differences in the generated hydrodynamic forces and moments. In order to eliminate this shortcoming, partly captive tests were designed. In these tests, a model is free to heave and pitch but is restrained in the other modes of motion.

If the partly captive tests are carried out for a combination of various heading angles with respect to the wave direction, fixed angles of heel and forward speeds, then a pattern of the "frozen" positions can be designed. The values of the total hydrodynamic force, generated by the wave at any instantaneous ship-wave configuration, can be interpolated between the values for the tested positions.

Only the influence of the eliminated motions (roll, sway, yaw, surge) on the velocity distribution in the surrounding fluid would not be accounted for [corresponding to A and N forces in equation (3)]. An evaluation of this influence can be performed by forced oscillation tests in the same waves or by theoretical considerations.

Summarizing, in the fully captive tests the total hydrodynamic exciting force contains Froude-Krylov force and wave diffraction force, while in the partly captive tests the hydrodynamic force consists of Froude-Krylov force and scattering force modified by the absence of some of the ship motions.

$$M_E = M_{F-K}(S, \Phi_S, t) + M_{SD}(S, \Phi_S, t) \quad (5)$$

The captive model tests should be performed in such a manner that the first three phases of the chain in Fig. 1 could be identified.

It becomes obvious that the first two elements of the "cause-result" chain must be the same for captive and free model tests, if any direct correlation between the hydrodynamic forces and the corresponding model response is to be defined. In other words, if the wave profile (and in consequence velocity potential), forward speed and the instantaneous shape of the hull immersed in this wave are the same in both cases, then there is a direct correlation between the hydrodynamic forces generated in captive modes and the corresponding components of free motion.

Identification of these elements requires a special test procedure which, beyond the measurements of motions and forces, should also satisfy the following conditions:

- Wave parameters must be continuously measured in the close vicinity of the model (but in the undisturbed field).
- Position of the model with respect to the wave profile has to be recorded continuously so that, for any time point, an instantaneous configuration of the immersed body in a wave can be identified.
- The program of captive model tests should contain a sufficiently wide range of fixed heading angles, heel angles, forward speeds, drift velocities and appropriate wave parameters so that a large, consistent grid of "frozen" positions can be constructed.
- A wide seakeeping basin equipped with a carriage and an appropriate wavemaking system must be used, such that the fastened model can be moved along a desired path in extremely steep, breaking waves.

3. Test techniques

The model experiments were carried out at the SSPA Maritime Consulting AB laboratory (Sweden). The facilities satisfied all the requirements and made the complex experimental program feasible.

According to the philosophy developed, the experimental program consisted of free-running, fully captive, and partly captive model tests. A detailed description of the test arrangements, procedures and instrumentation has been presented in [9]. The most important information on the test technique used is outlined below.

Free-running model tests

The objective of these tests was to provide detailed information on a ship's behavior in extremely steep/breaking, quartering waves with a particular focus on the dynamics of the capsize phenomenon.

The test technique and procedure assured a possibility of detailed analysis of the kinematics of ship capsizing and, at the same time, provided the conditions for the capsize process to be realistically modelled.

During the tests the model was completely free to move (cover picture). It was self-propelled and controlled by an autopilot of a proportional regulator type:

$$\delta = k(\psi - \psi_{Nom})$$

The range of rudder angles was ± 35 deg; the maximum rudder rate 15 deg/sec and the coefficient $k = 1$; rudder height = 0.125 m, length = 0.077 m.

Power supply to the model and all the signals from the sensors placed in the model were transmitted via a flexible cable to the carriage which was tracking the running model. The cable did not introduce any constraints to the model motions. If, occasionally, such a constraint occurred, it was detected and the results were eliminated from further analyses.

All components of the model motion were continuously measured and recorded. Roll and pitch were measured with a gyroscope and yaw with an electro-optical system (Selspot) which was also a base for the autopilot control system. The translatory motions were measured in the model moving reference system by accelerometers fixed in the centre of the model. Relative vertical motions of the water surface at both model sides were measured amidships with capacitance wave probes. Additionally, the rudder angle was recorded and the instantaneous forward speed of the model was measured with a Pitot tube located underneath the keel at midships. The waves were measured with one wave probe at a fixed position in the basin and another one mounted to the carriage and measuring the waves in the carriage moving reference system, in close vicinity to the running model.

The adopted reference system and the signs convention is presented in Fig. 2.

All the measured values were recorded by the carriage standard data acquisition system in a digital form with a sampling rate of 25 Hz.

The problem of the continuous recording of the relative position of the model with respect to the wave profile was solved by the implementation of a video recording system into the whole measurement setup. Two cameras were used simultaneously in order to allow observation of the model from two different perspectives. In addition, every second theoretical station was marked on the model sides and plainly visible draft marks were put on them. The time base of the video recording was synchronized with the main data acquisition system and therefore, it was possible to identify any instantaneous wave-model configuration by using a stop-picture technique ("frozen" position) and to relate it to the main records of the test. This technique was the key element in the motion analysis and

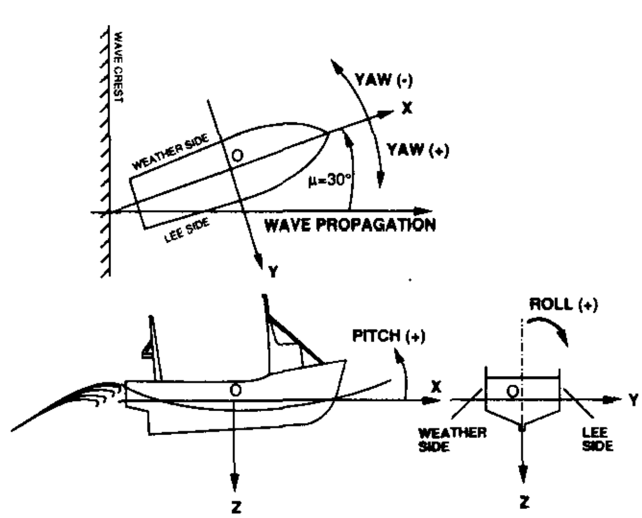


Fig. 2 Reference system in free-running model tests

in the process of relating the free test results to those of the captive tests. The accuracy of the still-picture analysis is 0.03 sec.

Fully captive model tests

In this test procedure, the model was connected to the carriage by a six component balance and was constrained in all modes of motion relative to the carriage. The model followed the carriage motion, being forced to move in waves in the horizontal plane with controlled forward speed and with required course angle with respect to the direction of wave propagation (Fig. 3). The mounting system provided the possibility of fixing the model at various heel angles up to 45 deg. The vertical position of the model at each angle of heel was adjusted so that constant model displacement in calm water was maintained. Drift speed was added in some runs, in order to study the influence of a lateral motion on the generated hydrodynamic forces while moving in waves.

The model was equipped with the same propulsion system as in the free running tests. The propeller revolutions were adjusted to a constant value corresponding to the model self-propulsion point in calm water.

The adopted coordinate system and the signs convention in the fully captive tests are presented in Fig. 4. The forces or moments in all the six modes were measured, that is, surge, sway, and heave forces, and the roll, pitch and yaw moments. The forward speed, drift velocity, heading angle and heel angle were the adjusted values. The waves were measured the same way as in the free tests. Furthermore, the free surface oscillations on both model sides were recorded by use of the same probes as in the case of the free tests and the same video recording system was used for tracking the instantaneous wave position with respect to the model (see Fig. 3).

Partly captive model tests

In the partly captive experiments, the model was free to heave and pitch but was fixed to the carriage in all other modes of motion. The model was attached to the carriage through a statically balanced frame containing a four component balance and was forced to move in the horizontal plane by the carriage motions with an adjusted speed and course with respect to the direction of wave propagation (Fig. 5).

Surge and sway forces, as well as roll and yaw moments, were measured by the four-component balance, while heave and pitch motions were tracked by a special lightweight arm. During the tests the model was mounted at various angles of heel up to 45 deg.

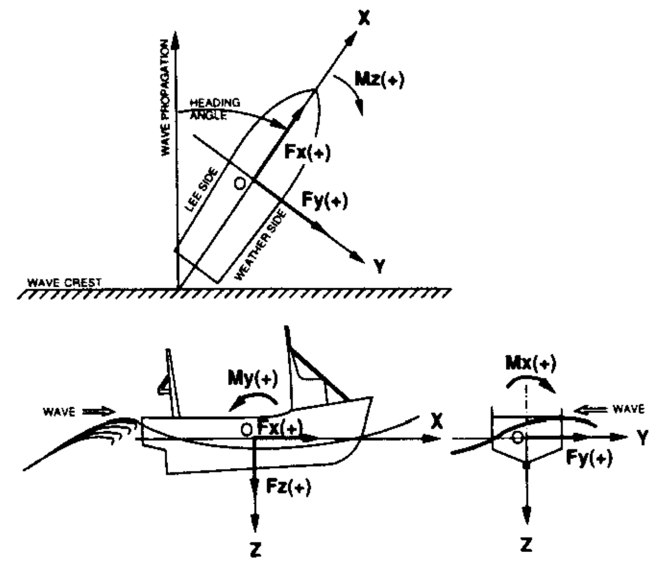


Fig. 4 Reference system in fully captive model tests

The model was prepared and ballasted as for the free-running tests. The displacement, position of the center of gravity, and the mass moments of inertia were correctly scaled. During the tests, the propulsion system worked with propeller revolution corresponding to the self-propulsion point in calm water.

The coordinate system and signs convention for the forces and moments are the same as for the fully captive tests, (Fig. 4), while the signs of heave and pitch motions are in agreement with the free-running tests (Fig. 2).

As in the case of the fully captive tests, the wave characteristics were measured in the moving system by one probe fixed at the carriage close to the model, at a known distance from it, and in the fixed reference system by another probe fixed in the basin. The relative motions of water at the model sides were measured with the same system as in the free model testing and the fully captive

Fig. 3 Fully captive model tests in breaking waves

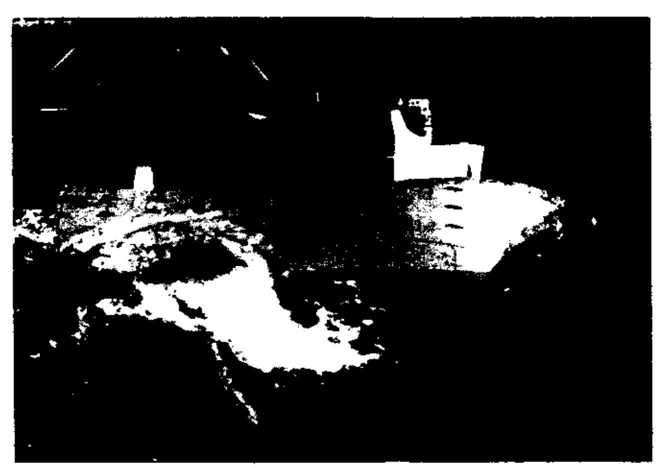


Fig. 5 Partly captive model tests in breaking quartering waves

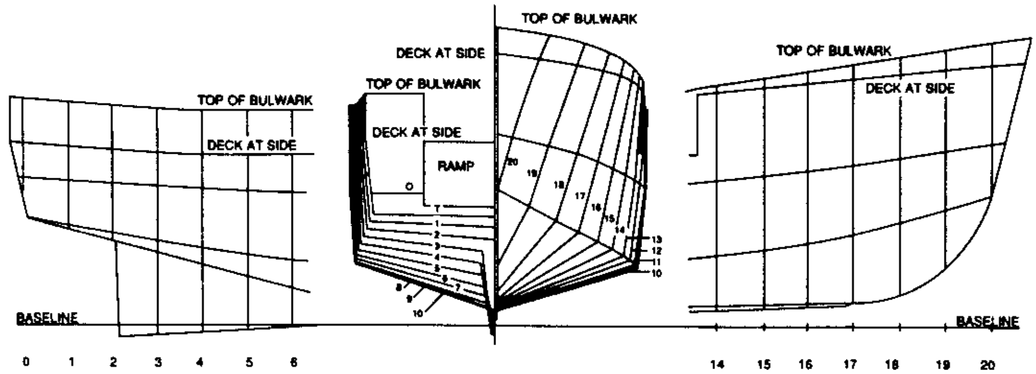


Fig. 6 Body lines of tested model

tests. The instantaneous position of the model with respect to a passing wave was tracked by the use of the video-recording system, synchronized with the main recording system as in the case of the previous model tests.

4. Model particulars

A typical small Canadian, hard-chine stern trawler of 19.75 m length was selected as a subject of the experimental studies. The body lines are presented in Fig. 6.

A 1:14 scale model was fabricated of fiberglass (GRP) and was fitted with bulwarks, freeing ports, superstructure and stern ramp, all correctly scaled. It also included a large centerline skeg and a single four-blade propeller / flat plate rudder arrangement.

Specific elements of the hull shape are:
—single hard chine along the whole body,
—flat, side-to-side, bottom in the stern part, sloping up from the keel at midship to the stern ramp,
—large skeg, and
—stern ramp.

Distribution of the hull volume to the deck and to the waterlines corresponding to the two tested loading conditions is presented in Fig. 7. Note in these graphs and body lines the large difference in the distribution of volume between the forebody and afterbody. The principal particulars of the model are given in Table 1.

Two loading conditions were selected for the testing: port departure (loading condition I) and full load (condition II), with two different stability characteristics for each. The particulars for these conditions are given in Table 2. The righting lever curves for each of the tested loading conditions are presented in Figs. 8 and 9.

It is worth noting that conditions IA and IIB satisfy the IMO stability requirements while IB and IIA do not [10].

Table 1 Principal particulars of model

Length overall, L_{OA} =	1.413 m[a]
Length on waterline, L_{WL} =	1.328 m
Beam, B =	0.435 m
Draft (molded), d =	0.190 m
Depth, D =	0.263 m
Bulwark height, h_N =	0.065 m
Scale 1:14	

[a] 1 m = 3.28 ft.

5. Test program

According to the conceptual frame developed, the experiments were split into three different categories and the program was organized in such a way that identification of the elements of the capsizing mechanism and detection of major factors which bring a ship to capsize were made possible.

Free-running tests

The tests with the free-running model were focused on investigations in quartering, close to breaking, and break-

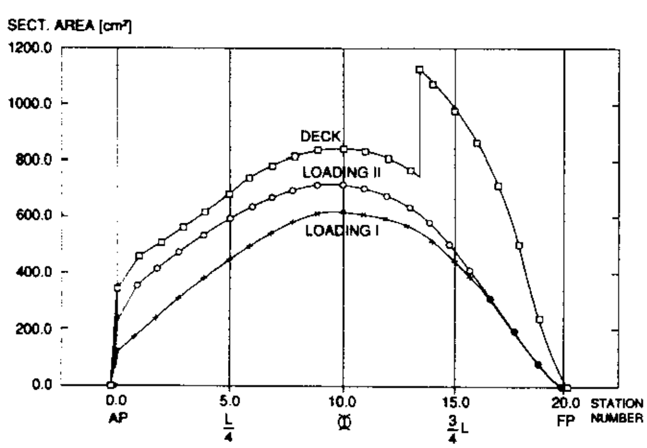


Fig. 7 Distribution of hull volume of tested model

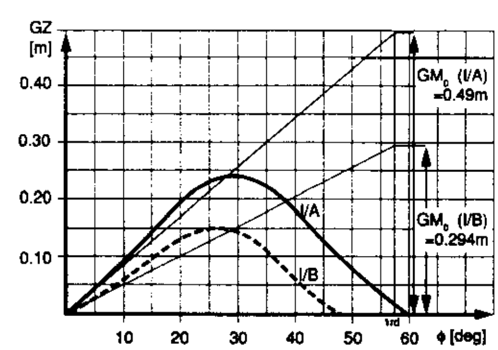


Fig. 8 Righting arm curves for tested port departure conditions

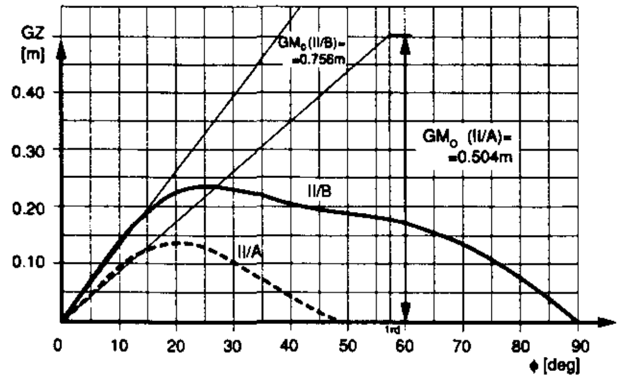


Fig. 9 Righting arm curves for full load conditions

ing waves. They were carried out in regular and irregular waves. In this case, the category of "regular wave" refers to waves with a constant period and a constant height, but with the wave profile not sinusoidal.

The regular waves were generated with a wave height to wave length ratio of 1:7 in order to achieve the maximum steepness and the breaking effect.

The irregular waves were generated according to the JONSWAP (Joint North Sea Wave Analysis Project) spectrum with two combinations of significant wave height and modal period, so that a pattern of large breaking waves could be formed frequently. The wave program was as follows:

Regular waves:

Nominal wave height, m	0.18 0.27 0.38
	0.44 0.50 0.65
Nominal wave period, sec	0.9 1.1 1.3
	1.4 1.5 1.7

Irregular waves:

JONSWAP spectrum ($\gamma = 3.3$)

Significant wave height, m	0.30 0.36
Modal period, sec	1.50 1.70

It is worth noting that the regular waves covered the range of heights which corresponds to 0.68 to 2.47 of the model molded depth, while the range of encountered frequencies covered the roll natural frequencies.

The tests were carried out for combinations of the following parameters:

Loading conditions:

Port departure: $GM = 0.035$, 0.021 m

Full load: $GM = 0.036$, 0.054 m

Forward speed, m/sec: 0.7, 1.1, 1.4

Heading angle, deg: 30 (nominal), 90

The program, which consisted of 117 runs, covered a wide range of possible dangerous situations, and many capsize events were recorded.

Captive tests

The tests with the captive model were concentrated on studies of the hydrodynamic forces generated at various model-wave configurations and on the influence of heading angle, heel position and lateral motion. The experiments were performed for one regular-wave condition and one irregular-wave spectrum:

Regular waves:

Nominal wave height 0.27 m

Nominal wave period 1.1 sec

Irregular waves:

JONSWAP spectrum ($\gamma = 3.3$)

Significant wave height 0.30 m

Modal period 1.5 sec

One loading condition was tested: Port departure IA, $GM = 0.035$ m. The parameters varied were:

Heading angle, deg:	0, 30, 40, 50, 60, 90
	(where 0 deg = following sea)
Heel angle, deg:	0, 10, 20, 35, 45
	(where 0 deg = upright position)
Forward speed, m/sec:	0, 0.7, 1.1, 1.4
	(0–10 knots in full scale)
Drift velocity, m/sec:	0, 0.2, 0.4, 0.6

The combinations of these parameters were formed in such a way that the interpolation of the results for other combinations within the covered range of the parameters can be made.

Table 2 Model loading conditions

Loading Condition[a]	Port Departure IA	Port Departure IB	Full Load IIA	Full Load IIB
Displacement, m^3	0.0531	0.0531	0.0657	0.0657
Draft AP, m	0.185	0.185	0.239	0.239
Draft FP, m	0.213	0.213	0.209	0.209
LCG fwd $L/2$, m	−0.009	−0.009	−0.058	−0.058
KG above BL, m	0.216	0.230	0.208	0.190
GM, m	0.035	0.021	0.036	0.054
k_{xx}, m	0.141	0.141	0.146	0.151
k_{yy}, m	0.310	0.312	0.310	0.313
k_{zz}, m	0.315	0.315	0.322	0.322
Roll period, sec	1.74	2.15	1.71	1.45
Heave period, sec	0.94	0.87	1.08	1.32
Pitch period, sec	0.97	0.99	1.05	1.02

[a] 1 m = 3.28 ft; 1 m^3 = 35.31 ft^3.

The fully captive and partly captive model tests were carried out according to a similar program. The number of runs in the captive testing amounted to 320.

All the results of the model tests were stored in the form of time histories. The heave, sway and surge acceleration of the free-running tests, which originally were recorded in the coordinate system fixed with the model, were converted into the absolute reference system and by double integration heave, sway, and surge displacements were determined.

The results of force / moment measurements in the captive tests were recalculated from the balance reference systems to the center of gravity of the model for loading condition IA.

Video records were carefully analyzed, and the detected positions of the wave crest with respect to the model were implemented to the time histories of motions and forces.

6. Ship kinematics in quartering waves

The experimental procedures and techniques provide the possibility of analyzing, in detail, a composition of the hydrodynamic forces and ship motions as a function of an instantaneous ship position relative to a passing wave.

A standard set of time histories resulting from the free-running model testing for the light loading condition is presented in Fig. 10. The translatory motions are presented in the inertial reference system; that is, surge and sway are horizontal while heave is vertical. The rotational motions are in agreement with the modified Euler's coordinates [6] where roll is a rotation about the X-axis (despite an instantaneous position of this axis in the space), pitch denotes an angle between the X-axis and the horizontal plane, and yaw angle is the angle between the projection of the X-axis on the horizontal plane and the nominal course direction.

The wave elevation is the encountered wave, measured by the probe moving with the carriage close to the running model.

The time points at which the model was in a wave trough (T), and when the wave crest reached the after perpendicular (AP), a quarter of the model length ($\frac{1}{4}L$), the midships (⊗), three quarters of the length ($\frac{3}{4}L$), and the forward perpendicular (FP), have been identified from the video records and marked on the time histories in the form of vertical lines.

In the studies of the mechanism of ship capsizing in quartering waves, it is essential to know what is the direction of the particular motions when a wave crest is passing along the hull, and how they are related to each other and with respect to the instantaneous position of the hull in the space and in the wave.

In order to facilitate the analysis, a sequence of situations occurring for the time points marked in Fig. 10 is presented in Fig. 11. The numerical values indicate the instantaneous position of the model in the adopted reference system while the vectors represent the instantaneous velocity in each mode of motion. The length of each vector is proportional to the represented velocity.

A ship advancing in quartering high waves performs a very characteristic composition of motions. The cycle of one wave action which is presented in Figs. 10 and 11 can be considered a good representation of such a composition for a ship without bulwark submergence and without water on deck. The short lasting exceedance of the bulwark edge at the lee side by the passing wave crest (see the record of channel 2) did not cause any significant changes in the motion characteristics and no water shipped on the deck.

In the wave trough the model reaches its lowest position, essentially without a trim angle and just starts recovering from the maximum weatherward heel. As a result of the motions on the back slope of the previous wave, the surge and sway velocities are directed toward the oncoming wave and the turning about Z-axis brings the model closer to a position perpendicular to the wave crests.

On the front slope of the oncoming wave the model starts to move upward and gets increasing trim by the head. At the same time the roll motion becomes very dynamic and the model changes its heel position from the weather to lee side. The sway, surge and yaw motions maintain their previous directions throughout the majority of the time.

When the wave crest reaches the stern, the model has a fairly large heel to lee side and dynamic roll increases the heel further. The model is in its extreme trim by the head.

The wave impact on the stern pushes the hull forward and aside, causing its dynamic turning about Z-axis toward a beam position. A significant sway toward lee side starts to develop and the forward speed increases. The wave crest reaches the quarter of the model length relatively quickly, increasing greatly the velocities of yaw, sway, and surge motions. The heel to lee side is still increasing.

When the wave crest is close to the midships, the model reaches its extreme up position, the trim becomes zero, and the roll attains the extreme heel to lee side. The dynamics of yaw, sway and surge is the highest at this moment. At the same time, the reduction of the restoring moment in the wave crest is the largest. This is the most dangerous moment for the stability safety.

In the case of the hull shape investigated, the position of the wave crest at the midships is accompanied by the largest increase of forward speed, combined with still large yaw and sway in the previous directions. The model gets a trim by the stern and starts to heave downward.

If a bulwark on the leeside is not submerged, the model starts to recover from the large heel. With the wave crest traveling forward, the velocity of the returning roll is increasing, while velocity of yaw, sway and surge is decreasing. At a certain time point, the yaw and surge motions change their directions.

When the crest reaches a halfway point between the midships and the forward perpendicular (that is, $\frac{3}{4}L$) the bow attains its highest position and is being strongly pushed by the wave toward the lee side. The model turns about Z-axis in the opposite direction than in the preceding phases, trying to decrease the course angle. At this moment, the hull is approximately in an upright position but rolls fast to the weather side. The forward speed drops down, thus increasing the relative velocity of the wave crest. In a short time the wave crest reaches the forward end of the body, and the model moves on the back slope of the wave. Shortly, the model gets to a wave trough and a new cycle of motion begins.

The time period during which a wave crest is traveling along the range of ship length, in particular between the stern and approximately $\frac{3}{4}L$, is the most important part of the motion cycle with respect to the possibility of a capsize.

A characteristic element in the composition of motions in quartering waves is a very unfavorable combination of roll, sway and yaw in conjunction with the ship position on a wave crest.

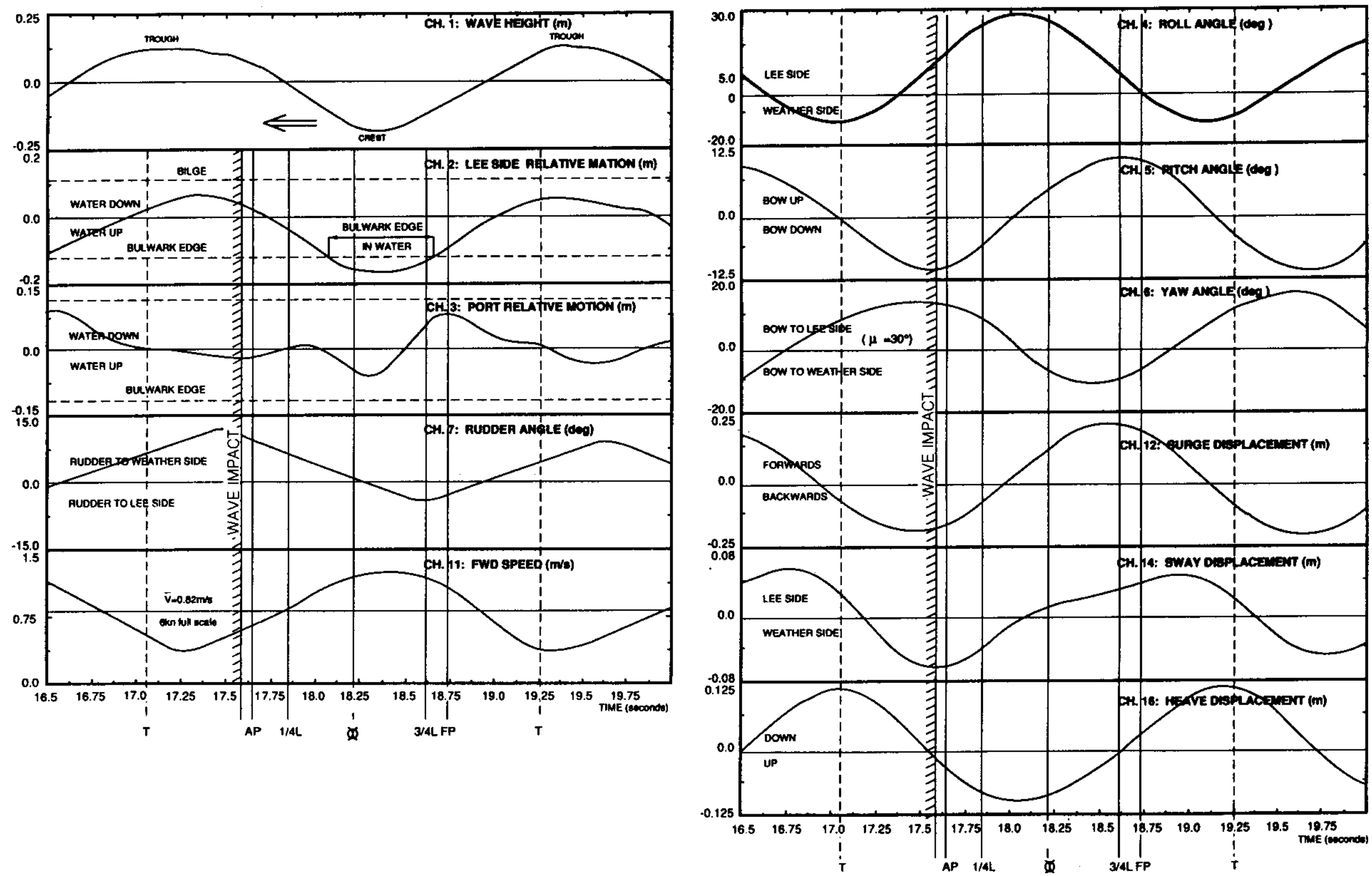


Fig. 10 Example of a time record from free-running model tests in quartering waves. Typical configuration of motion components during one wave cycle; run No. 13, condition I/A; heading angle $\mu = 30$ deg; forward speed $v \simeq 0.85$ m/s; nominal parameters of periodic waves: $H = 0.38$ m, $T = 1.3$ sec

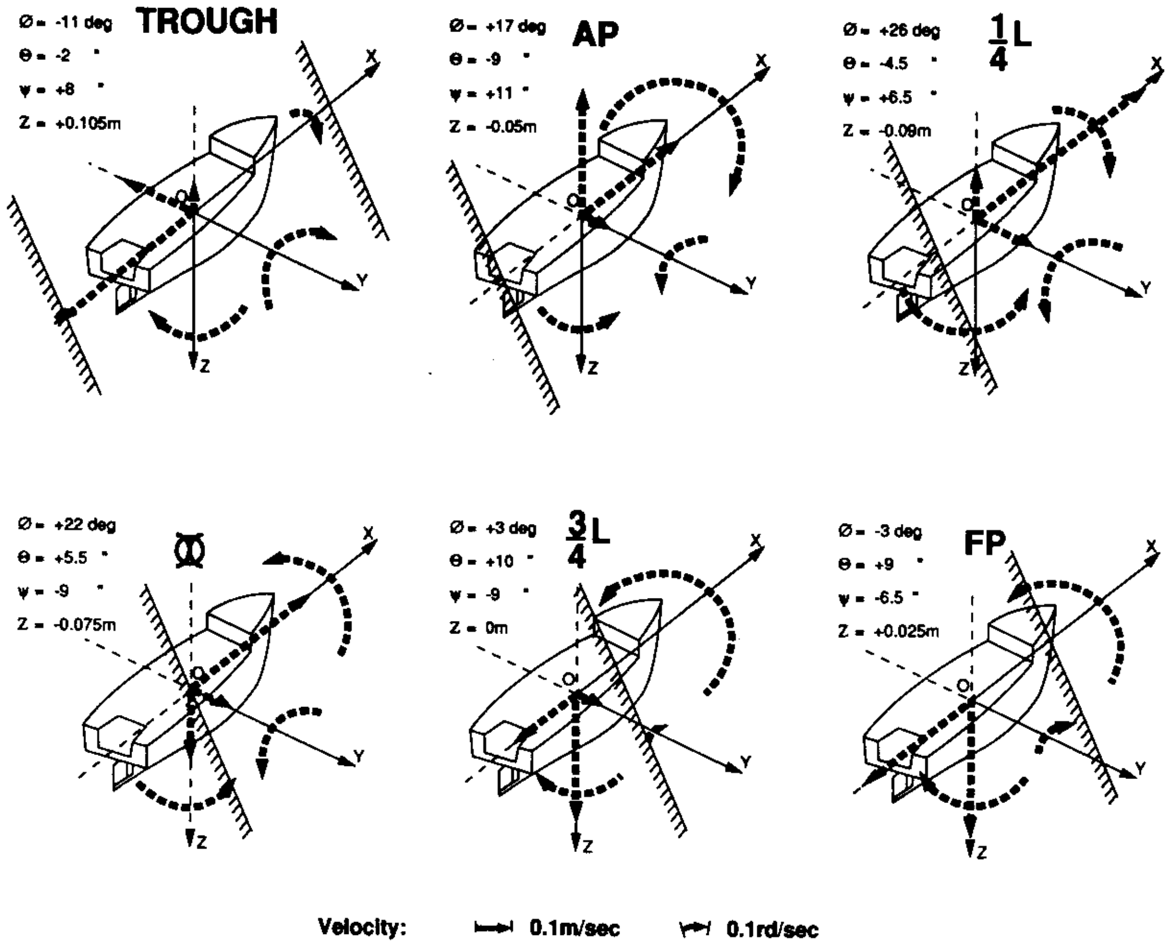


Fig. 11 Ship motion components in quartering waves free-running model test No. 13

After a wave impact, the stern is pushed forward and aside, and the ship undergoes fast yaw and sway motions to lee side with a simultaneous increase of heel angle. As a result of this combination, the after part of the deck edge at the leeside is moving down and sidewards, attaining a large lateral velocity.

At the same time, the wave crest is moving forward increasing the dynamics of the lateral motion of the after part of the hull, reducing the restoring moment, and increasing a chance of the bulwark and deck edge immersion at the lee side.

The increase in forward speed, caused by the wave impact and by the subsequent large surge, makes the duration of this dangerous situation relatively long. If the bulwark becomes submerged, the ship is under a threat of capsizing.

Note that, because of the surge motion, the time during which the model remains on a wave crest (wave crest between $\frac{1}{4}L$ and $\frac{3}{4}L$) is very long and in the case considered it constitutes over 70 percent of the time of the wave crest traveling along the model, and 35 percent of the whole cycle.

The roll is not symmetric. The amplitudes to lee side are about twice as large as those to weather side.

The model's behavior in beam waves was also examined. A fragment of time histories, recorded for the model in full load condition IIA, running with average speed 0.8 m / sec in periodic waves, is presented in Fig. 12. Similarly to the analysis of motions in quartering waves, Fig. 13 presents the sequence of instantaneous positions of the model in space and the corresponding velocities of the motions for the model in trough (T), at one quarter of the cycle (T / 4), when the wave crest is at the weather side (WS), at the central line (CL), at the leeside (LS), and for three quarters of the cycle ($\frac{3}{4}$T).

Because of a strong nonsymmetry of the fore- and afterbody of the vessel, small pitch, yaw, and surge occur during the motion in beam waves. However, the amplitudes are very small in comparison with the other motion components and do not have any significant influence on the nature of the ship behavior.

From the comparison of Figs. 12 and 13 with Figs. 10 and 11, it can be found that basically the composition of roll, sway, and heave in both cases is very similar. The essential difference occurs, obviously, in the shape of the immersed part of the body and in the whole configuration: immersed body-wave elevation.

Furthermore, the large portion of wave energy is absorbed by heave, and the phase of heave motion is such that it reduces the chance for a deep submergence of the bulwark. In addition to this, although the roll is even more nonsymmetric than in quartering waves, the phase of roll in relation to the wave profile is also advantageous. During the most critical phase of motion when the wave crest is

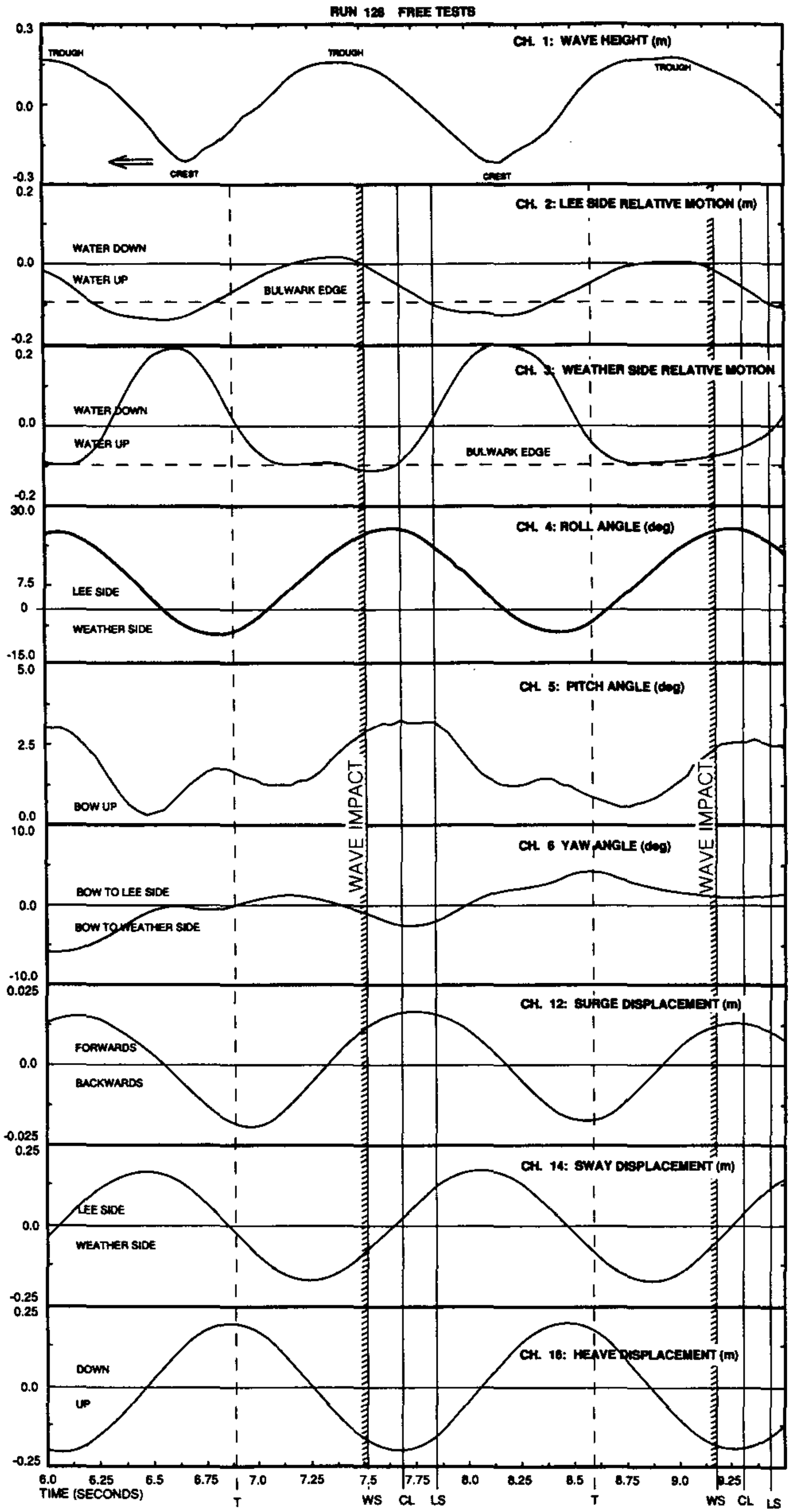


Fig. 12 Fragment of time record of test with free model running in beam periodic waves; run No. 128, condition II/A; forward speed v = 0.75 m/s; nominal wave parameters: H = 0.44 m, T = 1.4 sec

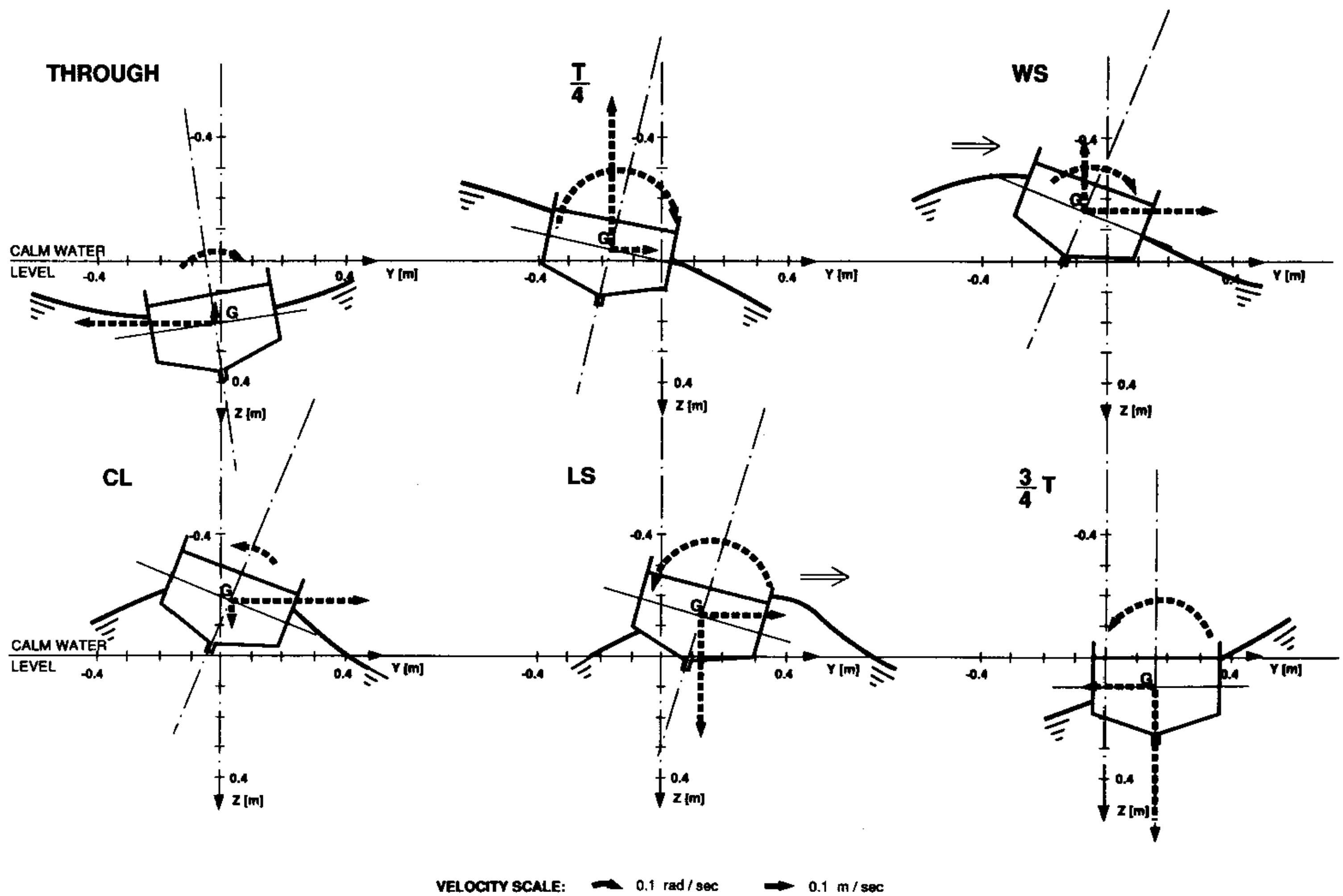


Fig. 13 Ship motion components in beam periodic waves. Free-running model test No. 128

directly acting on the body (WS, CL and LS in Fig. 13), the direction of roll motion is such that it prevents immersion of the bulwark.

7. Hydrodynamic exciting forces

The testing with the fully restrained model enabled study of the composition of the forces in well-defined conditions and analysis of the influence of the hull-wave configuration on the hydrodynamic forces created.

A fragment of the time record for a fully captive test without forward speed and without drift, with the model fixed in the upright position at a heading angle $\mu = 30$ deg, is presented in Fig. 14. The signs of the graphs correspond to the reference system represented by Fig. 4.

The position of the wave crest in relation to the model is marked in the graphs the same way as in the case of the free-running tests (T, AP, $\frac{1}{4}$ L, ⊕, $\frac{3}{4}$ L, FP, T). The same cycle of hydrodynamic exciting forces is presented in a vector form for the selected wave crest positions in Fig. 15.

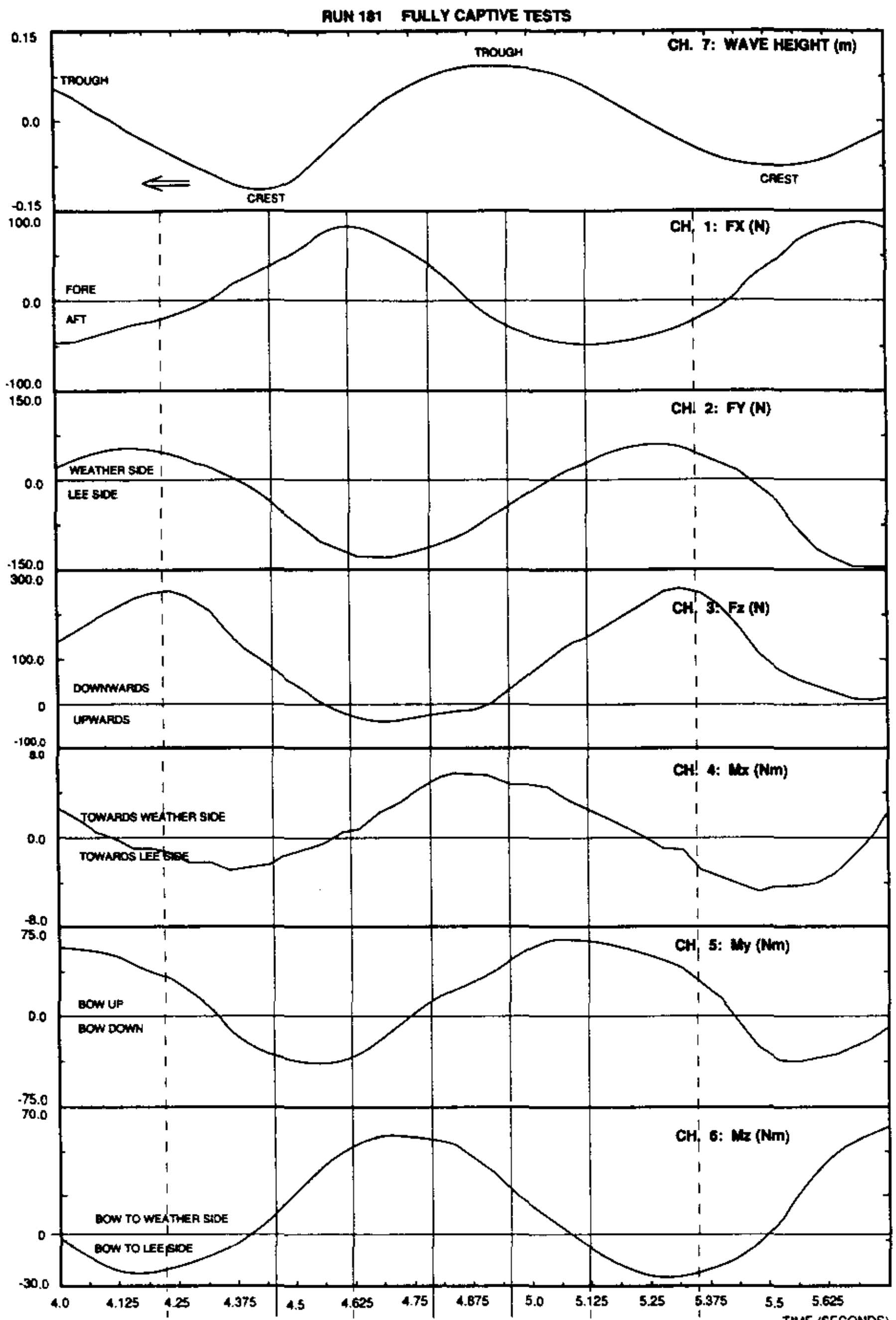


Fig. 14 Components of hydrodynamic force and moment on fully restrained model in quartering waves; fully captive test No. 181; condition I/A; forward speed $v = 0$; heel angle $\phi = 0$; heading angle $\mu = 30$ deg; drift velocity = 0; periodic waves: $H = 0.27$ m, $T = 1.1$ sec

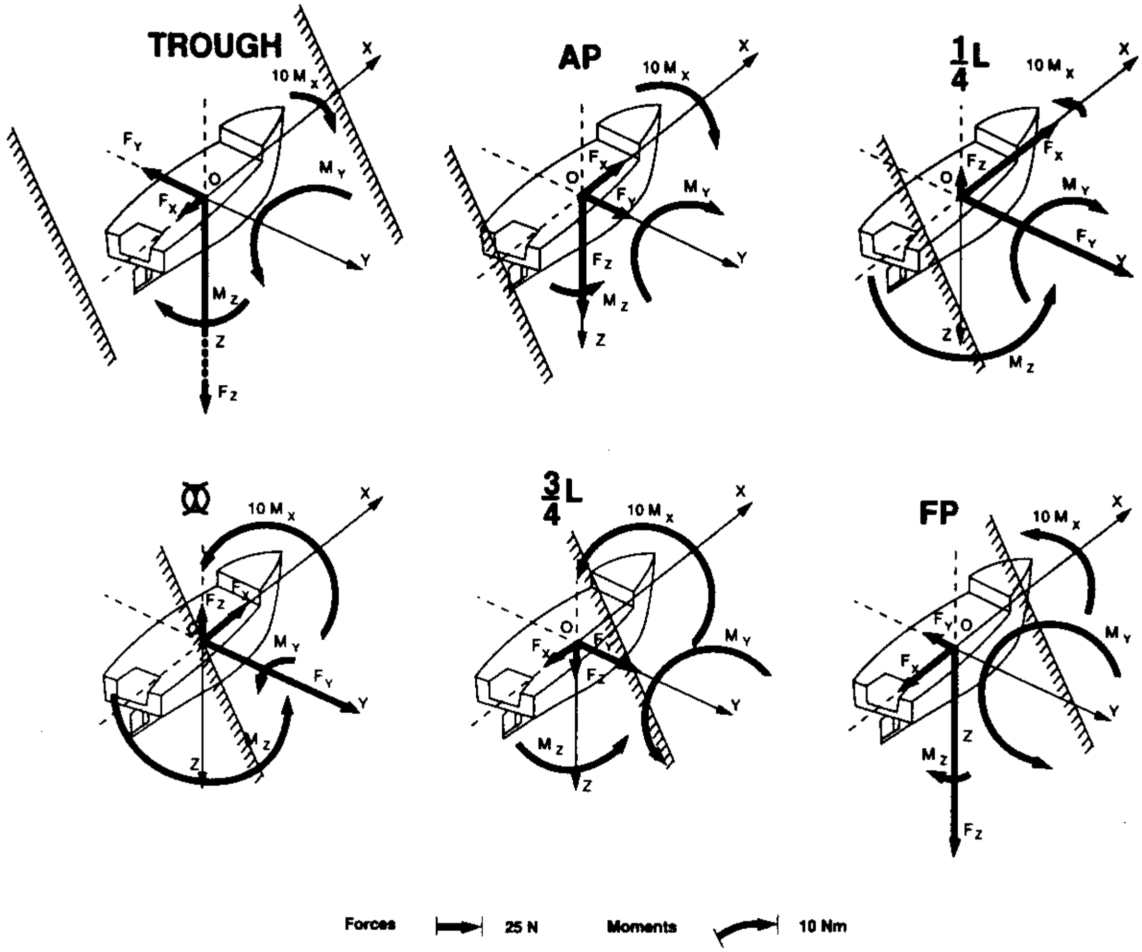


Fig. 15 Forces and moments on fully captive model in quartering waves (run No. 181)

In order to make the composition of the hydrodynamic exciting forces directly comparable with the corresponding motions in Fig. 11, the assumption is made that the wave is coming from the port side (as in the case of the free tests) and not from the starboard, as it was in the captive tests (compare Figs. 2 and 4). So, in comparison with Fig. 14, the signs of F_y, M_x, and M_z in Fig. 15 have been changed to the opposite.

The presented composition of the hydrodynamic forces is very characteristic for a ship under the action of a quartering wave.

When the model is situated on the front slope of the oncoming wave (T-AP), the moment M_x constitutes a heeling moment and endeavors to heel the body to the lee side. The composition of the longitudinal (F_x) and lateral (F_y) forces with the yaw moment (M_z), which, in the wave trough, was a result of the action of the back slope of the previous wave, changes its direction to the opposite. The forces F_x and F_y now act forward and to the lee side, respectively, while the M_z moment pushes the stern to lee side. The pitch moment M_y tends to trim the model to the "bow down" position and the heave force F_z, which is still directed downward, is decreasing. This characteristic composition of forces persists until the wave crest reaches almost $\frac{1}{4}$ L.

The heeling moment M_x attains its extreme value when the wave crest approaches the stern. The extreme value of M_y occurs closely before the wave crest reaches $\frac{1}{4}$ L, and of F_x, when the crest is at $\frac{1}{4}$ L.

After the wave crest passes one quarter of the model length, the M_x moment changes its direction and becomes a restoring moment. The composition of M_z, F_x and F_y remains the same as before, although F_x starts to decrease.

During the wave traveling between $\frac{1}{4}$ L and midships, the sway and heave forces and the yaw moment attain their extreme values. At the same time, the pitch moment M_y changes its sign, tending to trim the model to "bow up."

When the wave crest is between ⨂ and $\frac{3}{4}$ L, the restoring moment (M_x) reaches its maximum value, while F_x force changes its direction and starts to push the model aft.

When the model's bow is on the crest, the composition of the forces is characteristic for the action of the back slope of the wave: the model is being pushed aft and to the weather side, the yaw moment endeavors to turn the model to a "following waves" position, and M_x acts toward the weather side.

It follows from the above discussion that the characteristic composition of the roll and yaw moments and the sway and surge forces is consistent with the corresponding motions in the free running situation. The directions of the motions follow the directions of the appropriate forces.

The situation is different with respect to heave and pitch. The applied restraints which eliminate the buoyancy self-adjustment mechanism make the conditions of the measurements of the heave force and pitch moment significantly different from the conditions in the free-running situations.

The strong nonsymmetry of the wave profile (steep crest, flat trough) and of the model shape with respect to the waterline resulted in a strong shift of the F_z curve relative to the zero level. This situation obviously affects the rest of the measured forces.

These difficulties are eliminated in the partly captive tests, where the model is free to heave and pitch. As the model can adjust its vertical and trim positions in order to maintain its buoyancy and the longitudinal balance in waves, the measured forces in the remaining captive modes more closely represent the real forces which occur during a completely free motion.

A fragment of a time record, representing one cycle of a wave action in a partly captive test, is presented in Fig. 16.

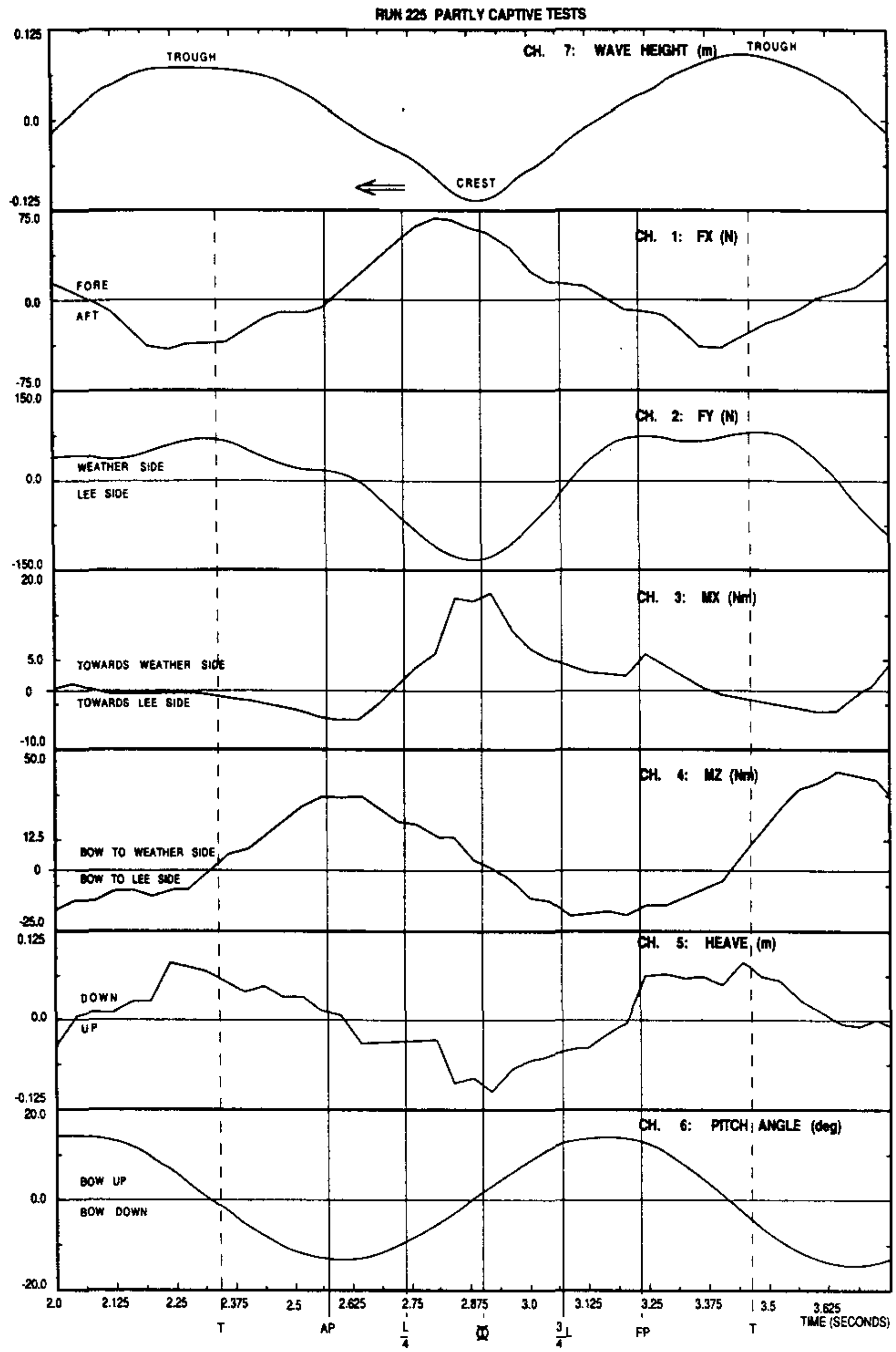


Fig. 16 Forces and motions in the partly captive test in quartering waves; test No. 225; condition I/A; forward speed $v = 0$; heel angle $\phi = 0$; heading angle $\mu = 30$ deg; drift velocity $= 0$; periodic waves: $H = 0.27$m, $T = 1.1$ sec

As for the fully captive tests, the composition of the hydrodynamic exciting forces and the free motions for the given wave crest positions has been transformed according to the assumption that the wave is coming from the port side, and presented in a vector form in Fig. 17. This makes the comparison with Figs. 11 and 15 easier.

Comparison of the heave and pitch motions in the partly captive test (Fig. 16) with those in the free-running test (Fig. 10) indicates a very good qualitative agreement despite the elimination of roll, yaw, sway, and surge motions in the partly captive test.

Bearing in mind that the small differences between the two cases reflect the difference in the wave profiles, and the fact that the partly captive test was performed at zero forward speed, it can be stated that heave and pitch motions in the partly captive tests represent very well the same motions in the free tests.

Thus, in the partly captive tests, the factor which most greatly affects the Froude-Krylov forces as well as the scattering effects (that is, the restraint in heave and pitch) has been eliminated.

The composition of the hydrodynamic exciting forces depends on the change of wave crest position in the manner described in the following. On the front slope of an oncoming wave, the model moves up and gets increasing trim by the head. The increasing roll moment (M_x) is a heeling moment which endeavors to heel the model toward the lee side, while the yaw moment (M_z) attempts to turn the model toward the beam position. The surge and sway forces which are still directed aft and to weather side, respectively, decrease rapidly and shortly change their directions.

After the wave crest reaches the AP, the model is in its maximum trim by the head, the stern is pushed strongly aside (toward the lee side) and forward, and the roll and yaw moments, which endeavor to heel leeward and turn the model to beam position, reach their extreme values.

This configuration persists during the time of wave crest advancing to about a quarter of the model length ($\frac{1}{4} L$) when the roll moment changes its direction, and tends to heel the model to the opposite direction (to weather side); that is, it acts as a righting moment.

The model is being strongly pushed forward and to the lee side together with turning to beam position all the time when the wave crest is moving between the stern and midships.

When the wave crest is in the vicinity of midships, the yaw moment changes its direction and starts to force the model to turn to the following wave position. At the same time, the sway and surge forces and the roll moment reach their maximum values. The model is in the highest vertical position and on even keel.

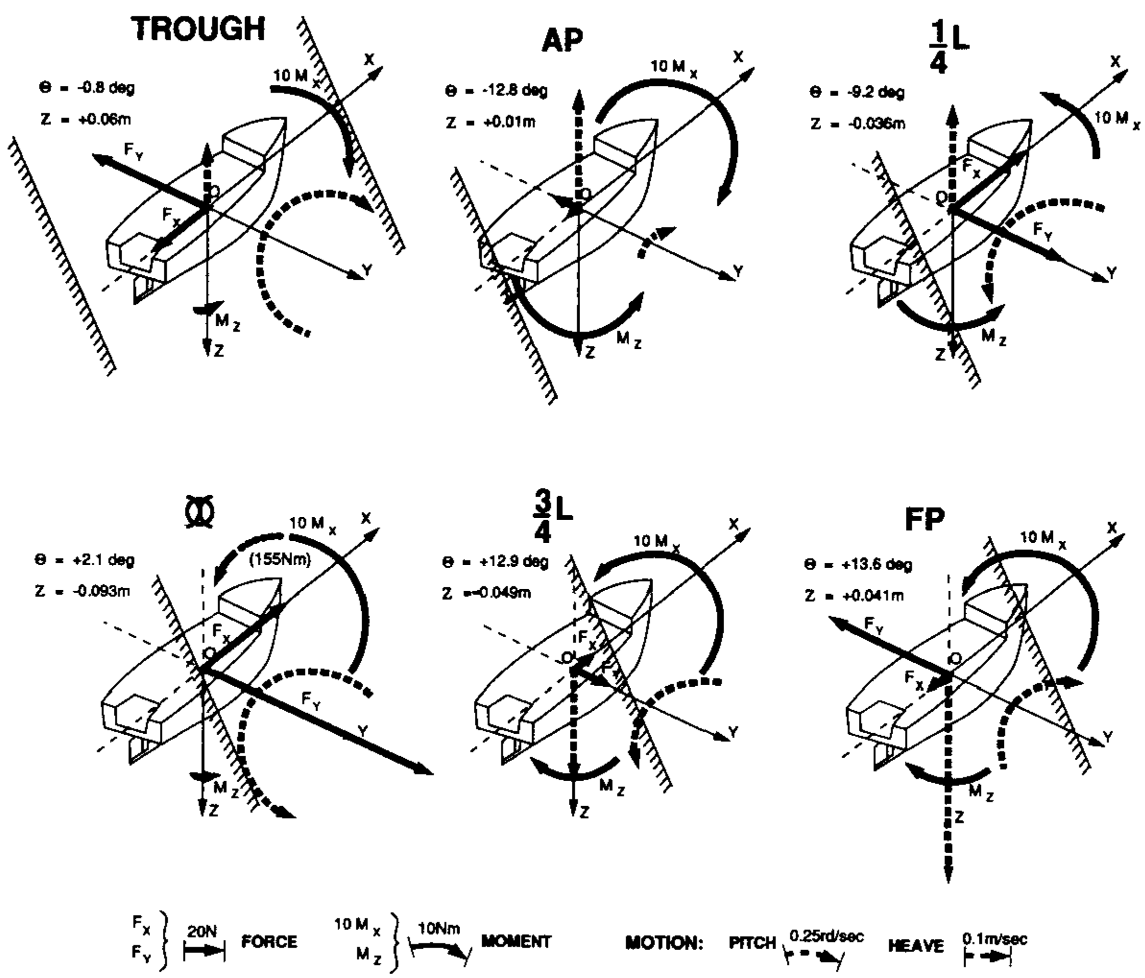


Fig. 17 Forces and motions in a partly captive test in quartering waves (run No. 225)

During a wave advancing between the midships and approximately half of the distance to the forward perpendicular (that is, $\frac{3}{4} L$), the model is still being pushed to lee side and forward. The heave is directed down, while the bow goes up.

After a wave crest has passed that distance ($\frac{3}{4} L$), the bow goes up and is strongly pushed toward the lee side, and the sway and surge forces reverse their directions shortly afterwards.

At the forward perpendicular (FP) the configuration of the forces is typical for the action of the back slope of a wave. The model moves down and the trim by the stern decreases. The roll moment acts weatherward, while the yaw moment endeavors to turn the model to a position perpendicular to the wave crest. The model is being pushed aft and to the weather side.

It is worth noting that the hydrodynamic forces are not symmetrical, relative to their zero lines. In both fully and partly captive tests, the sway force F_y toward the lee side is larger than toward the weather side, the surge force F_x is larger when directed forward, and the yaw moment M_z is significantly greater when tending to turn the stern to the lee side (bow to weather side).

This should be attributed to the wave impact and to a nonsymmetry of the wave profile. Surprisingly, the nonsymmetry in the roll moment M_x is such that it reaches larger values when acting as a restoring, rather than a heeling, moment.

The composition of the acting hydrodynamic forces and their transformations, caused by the traveling of the wave crest along the hull in the partly captive tests, is consistently compatible with the corresponding patterns of motions in the free-running tests. For instance, when the roll moment M_x acts toward lee side (from the trough to $\frac{1}{4} L$ in Fig. 16), the model rolls from the weather to lee side in the free tests (Fig. 10), and changes the direction of roll shortly after the roll moment started to act in the opposite direction. The same good agreement in the directions of the forces and motions, and the consistency with respect to the wave crest position, occurs in the case of all the remaining forces and the corresponding motions.

It is interesting that despite the significant difference in the shape of the immersed body, there is also a good qualitative agreement between the partly and the fully captive test results, as far as M_x, M_z, F_x and F_y are concerned.

The consistency and the good agreement between the results of the partly captive and the free-running model tests prove the pertinence of the basic assumptions of the philosophy of the captive tests. They confirm that, despite some motion restraints, the configuration of the hydrodynamic forces, which are generated on the model in the partly captive tests, is qualitatively the same as that in completely free motion. This means that conclusions which can be derived from the captive tests are applicable (with appropriate qualifications) to the analyses of the dynamics of model capsizing during the free-running tests.

The presented compositions of the hydrodynamic exciting forces were obtained by the measurements on the restrained model without forward speed, for a constant heading angle ($\mu = 30$ deg), and at the upright position. Obviously, forward speed and a variation of heading and heel angles result in changes of the measured forces. However, a detailed analysis of the influence of these parameters on the hydrodynamic forces exceeds the scope of this paper.

8. Analysis of capsize phenomena in quartering waves

The program of experiments with the model running freely in waves covered a wide range of possible dangerous situations. The results provide insight into the physics of ship behavior in extreme waves and yield evidence of the influence of some factors on ship susceptibility to capsizing in quartering seas.

Two distinctly different ship displacements were tested: light load condition I (port departure), and full load condition II (designed maximum displacement).

Two stability conditions for each displacement were selected in such a way that, in one case, the ship just satisfied the existing, commonly used IMO stability criteria (conditions I / A and II / B in Figs. 8 and 9), while in the other case the GZ curves were significantly below the required values (conditions I / B and II / A). The unsatisfactory righting lever curves were almost identical for both displacements, while those which satisfied the criteria differed between themselves for the heel angles larger than 40 deg (different range of positive GZ).

The experiments with the free-running model revealed a significant qualitative difference in a ship behavior at the light and the full load conditions.

In the case of the model running in relatively smaller waves, when there was no significant shipping of water on deck and no bulwark submergence, the characteristic composition of the motions in quartering waves, which was discussed in Section 6, occurred for both ship displacements despite the shape of the GZ curves. Although the intensity and the amplitudes of the motions were different for the two displacements, the character remained the same and the pattern of motions presented in Figs. 10 and 11 can be considered as a typical composition of ship motions in quartering seas. In the case of extreme waves, however, the model behavior was significantly different for the two displacements.

At the light condition, the relatively high freeboard gave protection against intensive shipping of water on deck, and provided reasonable stability even at a moderate initial metacentric height (GM_0 for the I / A condition). However, the model was very responsive to wave impacts and moved very dynamically with large-amplitude motions. The model broached very often and had difficulties with course-keeping. Large, dynamic lateral motions occurred frequently and created specific dangerous model behavior if, at the same time, the bulwark submerged.

At the full load condition the mass of the model was much larger and the freeboard was very small. These two factors affected strongly the behavior in waves. The hull was deeply seated in the water. The speeds and the amplitudes of the motions were much smaller than in the previous case. The model kept on course better, and the broaching occurred less frequently than in the case of the light condition. Owing to the low freeboard, the water shipped on deck frequently and in large amounts. The open stern ramp made this phenomenon even more intensive, resulting in the accumulation of water on deck in some cases, and strongly affecting the model's behavior in waves.

About the same number of tests were carried out for each loading condition.

At port departure condition I / A, the model survived the action of the waves with the nominal wave height up to about twice the molded model depth. However, difficulties started to occur at the runs with high forward speed at these wave heights. In the higher waves, the model experienced serious difficulties at slower speeds and capsized when running at high speed.

At the light load condition with the insufficient GZ curve, the model moved safely only in the smallest waves and had difficulties when running with greater speed in waves with a height approximately the same as that of the model's depth. In the higher waves, the model always capsized, irrespective of the magnitude of forward speed, both in regular and irregular waves.

The full load condition with the stability curve II / B appeared to be safe in all of the tested wave conditions. However, with the worse stability represented by the GZ curve II / A the model started to capsize in waves of height approximately 0.7 of model depth. Contrary to the light load condition, the lower speed appeared to be more dangerous than the higher one. Running with high speed, the model survived the action of the waves in which it capsized when moving at the lower speed.

The tests revealed that beyond the poor stability at conditions I / B and II / A, the mechanism which brought the ship to capsize was different at the two tested displacements.

While the water on deck had a decisive influence on the course of behavior at the full load conditions, the dynamics of motions and the bulwark submergence appeared to dominate the behavior at the light load conditions.

Various types of capsizing were recorded, some of which represent very clear examples of some characteristic behavior with dominating phenomena generated by a specific combination of certain factors, while some others contain a mixture of various elements occurring in other types. As a result of the tests

—poor stability and exposure to impact of breaking waves;
—stability reduction on a wave crest,
—shipping and accumulation of water on a deck, and
—effects of the submergence of the bulwark.

were identified as the most distinct situations which may bring the ship to capsize in quartering waves.

While in general the first three scenarios had already been addressed in some studies, the role of a bulwark submergence had not been analyzed before.

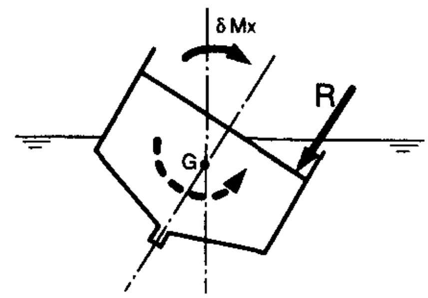
The examples which represent the above-mentioned capsize events are discussed next.

Influence of bulwark submergence on ship susceptibility to capsizing

An immersion of the deck edge and the upper edge of bulwark causes radical changes in the configuration of hydrodynamic forces and, in effect, in the character of ship motions. The hydrodynamic phenomena, which are generated by the movement of the submerged part of the deck and the bulwark, are very complex and have not yet been investigated or mathematically described. Some distinct elements of these effects have been revealed during the experiments.

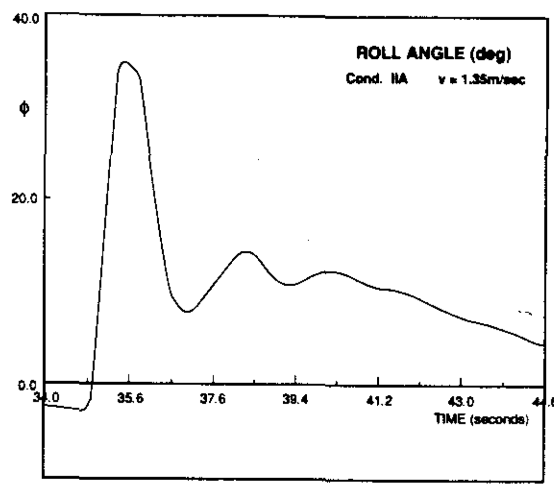
The bulwark submergence causes radical alterations in the roll motion. A hydrodynamic reaction is generated on the immersed part of the deck and on the bulwark during roll motion. This reaction constitutes a resistance of the surrounding water to the hull motion. The reaction force R creates a moment δM_x relative to the center of gravity G [Fig. 18(a)]. This moment counteracts the ship restoring moment. The resistance to the motion of the immersed part of the deck is usually so large that the generated moment δM_x prevents the ship from the usual rolling back

A)



ROLL MOTION WITH A SUBMERGED BULWARK

B)



DECAY TEST WITH THE BULWARK SUBMERGED.

Fig. 18 Influence of bulwark submergence on roll motion

to the vertical position. Such behavior was observed during the decay tests in calm water, with the model running at initial inclinations greater than the angle of bulwark submergence.

An example of the roll record from these tests is presented in Fig. 18(b). After the release, the model started to recover, but the reaction R reached, at a certain time point, a value large enough to stop further model motion. The model then made a few oscillations around this heeled position, and subsequently returned slowly to the upright position. This interruption and the delay in the recovery motion can have a critical consequence if a ship is moving in waves.

The influence of bulwark submergence becomes more emphatic if a ship executes lateral motions. As a result of a lateral movement of the hull, the submerged part of the deck is being forced to plough under the water. The resulting pressure on the submerged part of the deck and the bulwark generates a hydrodynamic resistance to the motion, and the resultant force (R) creates an additional moment, $\delta M_{x\varphi}$ which tends to increase the heel angle [Fig. 19(a)].

The generalized hydrodynamic reaction and, in effect, the additional heeling moment depend on the size and shape of the immersed part of the deck and bulwark, on

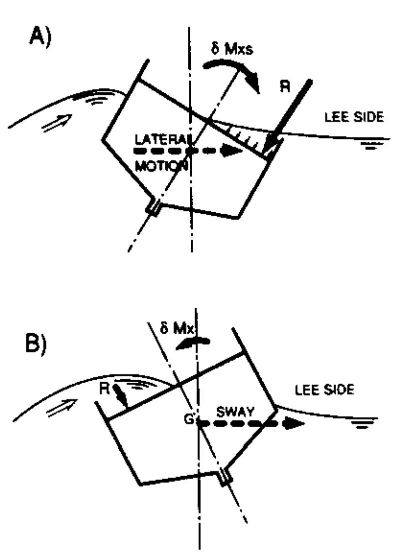


Fig. 19 Hydrodynamic effects generated by lateral motion during bulwark submergence

the heel angle, and on the velocity of the lateral motion relative to the surrounding water. The larger the part of the deck deeply immersed in water and the relative velocities in the lateral motion, the larger is the hydrodynamic reaction generated on the bulwark and on the submerged part of the deck. If the lateral motion during ship movement in waves is directed leeward and the bulwark at the lee side becomes submerged, the additional moment δM_{xs} generated is a heeling moment and adds to the wave action [Fig. 19(*a*)].

If it accidentally happens that the weatherside bulwark becomes submerged during a wave crest action and the ship is in weatherward heel position, the generated additional hydrodynamic moment δM_x counteracts the wave heeling moment, and the lateral motion toward the lee side reduces the reaction R and, in effect, also the δM_x moment [Fig. 19(*b*)]. As the leeward lateral motion also reduces the wave heeling moment, the configuration of the hydrodynamic forces created may result in the ship remaining at the heeled position (so-called pseudo-static angle of heel).

The difference between the Fig. 19(*a*) and 19(*b*) cases provides some explanation of why, during some reported model tests in beam waves [11, 12], the low-freeboard model which was heeled to the weather side and systematically subjected to water shipping on deck, never fully capsized to the weather side during the tests in beam waves, but did capsize on a next wave if, accidentally, a large wave impact heeled the model with the water on deck to the lee side.

The dangerous effect of the hull lateral motion while the bulwark is submerged consists not only in the generating of an additional heeling moment, which increases the leeward heel angle, but also has a substantial influence on the other motions.

The hydrodynamic effects created by the underwater ploughing movement prevents the bulwark and the deck edge from coming out of the water. This causes local restraints to the hull motion. If, simultaneously with a fast lateral motion, and with the bulwark submergence, a fast heave motion directed upward is forced by the wave action, the restrained deck edge causes the body to turn

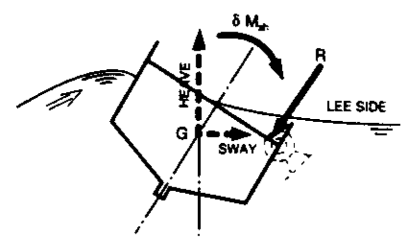


Fig. 20 Pivot-like effect caused by bulwark submergence, lateral motion and heave

about a longitudinal axis located close to the bulwark (Fig. 20).

As a result, the submerged bulwark and the deck edge act like a pivot at some phases of the motion when the dynamics of motions are very intense (this characteristic phenomenon has been symbolized by a pivot mark in Fig. 20). The phenomenon causes additional coupling effects between the lateral motion, heave, and roll, which create an additional heeling moment due to heave (δM_{xH} in Fig. 20).

The restraint of the motion of the submerged bulwark and, as a result, the preventing of the ship from rolling back to the vertical position, has also another negative influence on stability safety. If this restraint lasts long enough and causes the ship to remain in a heeled leeward position at an angle ϕ^* (Fig. 21) until the next wave crest reaches the hull, then the potential restoring energy of the ship is significantly reduced.

Assuming that the *GZ* curve reflects, to some extent, the restoring potential energy of the ship, the new zero level (0′) of this energy is established due to the heel angle ϕ^* (Fig. 21). It can be seen that only dynamic action of a significantly smaller wave can be counterbalanced by the ship in this configuration.

Furthermore, if the ship remains in the restrained heeled position, the initial conditions of the next wave action are altered. The whole energy of wave impact is applied to the ship with the bulwark already submerged. As a result, all the negative effects generated on the submerged part of the deck are significantly enhanced, and the phenomenon lasts much longer than during the first wave action. As a result, the leeward heel angle increases further, threatening the ship with capsize.

In order to confirm these—to some extent, intuitive—analyses, part of the captive tests was dedicated to examining the hydrodynamic forces generated on the hull when moving in waves with the lee side bulwark submerged and with leeward lateral motion. Various constant drift velocities toward the lee side were used to simulate the lateral motion of the ship after a wave impact. Fully

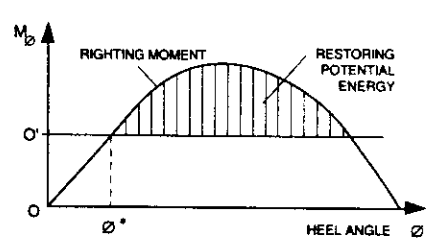


Fig. 21 Reducing effect of bulwark submergence on ship potential restoring energy

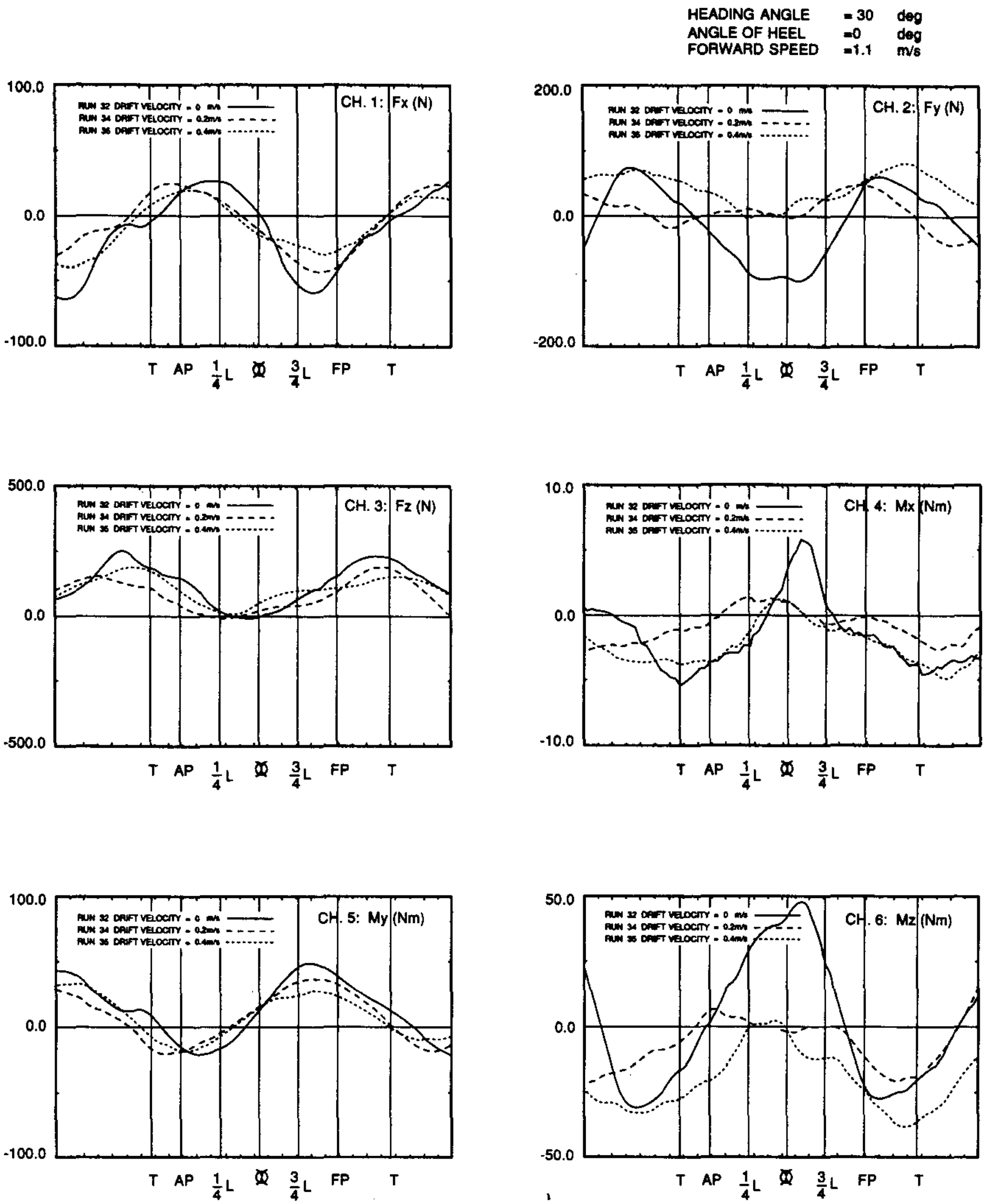


Fig. 22 Influence of lateral velocity on hydrodynamic forces and moments generated on fully captive model in quartering waves

captive and partly captive tests were carried out for various fixed heel angles so that the bulwark edge was above the water surface, or was submerged to various depths.

An example of the results for the fully captive model in the upright position, running in the quartering waves with a forward speed 1.1 m / sec, is presented in Fig. 22. The components of the hydrodynamic force, generated during one cycle of wave action on the model subjected to two drift velocities and without the drift, were collated as a function of an instantaneous position of a wave crest relative to the hull.

The differences which were caused by the difference in the wave profiles of the test runs were reduced by rescaling the values of the forces proportionately to the wave heights. The basis for the comparison is the instantaneous position of the acting wave crest.

It can be seen that the leeward drift reduces the amplitudes of the hydrodynamic forces on the fully restrained model, which runs in the upright position. Significant differences due to leeward drift can be noticed in the sway force (F_y), yaw moment (M_z) and roll moment (M_x), when the model moves on the wave crest.

The significance of the bulwark and deck edge submergence, combined with a leeward lateral ship motion in quartering waves, can be evaluated on the basis of the results presented in Fig. 23. The three graphs present the roll moment M_x for three different heel angles: 0, 20 and 45 deg. In the upright position the bulwark edge is practically almost all the time above the water surface; at the heel of 20 deg the bulwark is submerged when the crest is passing along the model length; and at the heel of 45 deg the lee side bulwark is deeply submerged at all times.

The dramatic alteration of the roll moment appears already at the heel angle of 20 deg. At this angle, the M_x moment is always positive if there is no lateral motion (drift velocity = 0), which, according to the sign convention for the captive tests (see Fig. 4), means that the moment acts in the opposite direction to the waves, that is, constitutes a restoring moment. The static righting moment causes this large shift of the M_x moment in waves.

If the model is forced to drift toward the lee side, then the hydrodynamic effects illustrated by Fig. 19(a) occur and the leeward heeling moment is generated. This moment reduces the moment M_x. At the drift velocity 0.2 m / s the restoring action of the M_x moment is practically eliminated and, for any faster drift, M_x always acts as a heeling moment, which endeavors to increase the angle of the heel. The larger the drift velocity, the greater the magnitude of the generated heeling moment.

At the heel equal to 45 deg, a qualitative change of the M_x curve, in comparison with that of the upright position, can be observed. The M_x curve is reversed, and the maximum—which occurs when a wave crest reaches the midship zone at the upright position—becomes a minimum at 45-deg heel. However, the generation of the additional heeling moment is also clearly revealed.

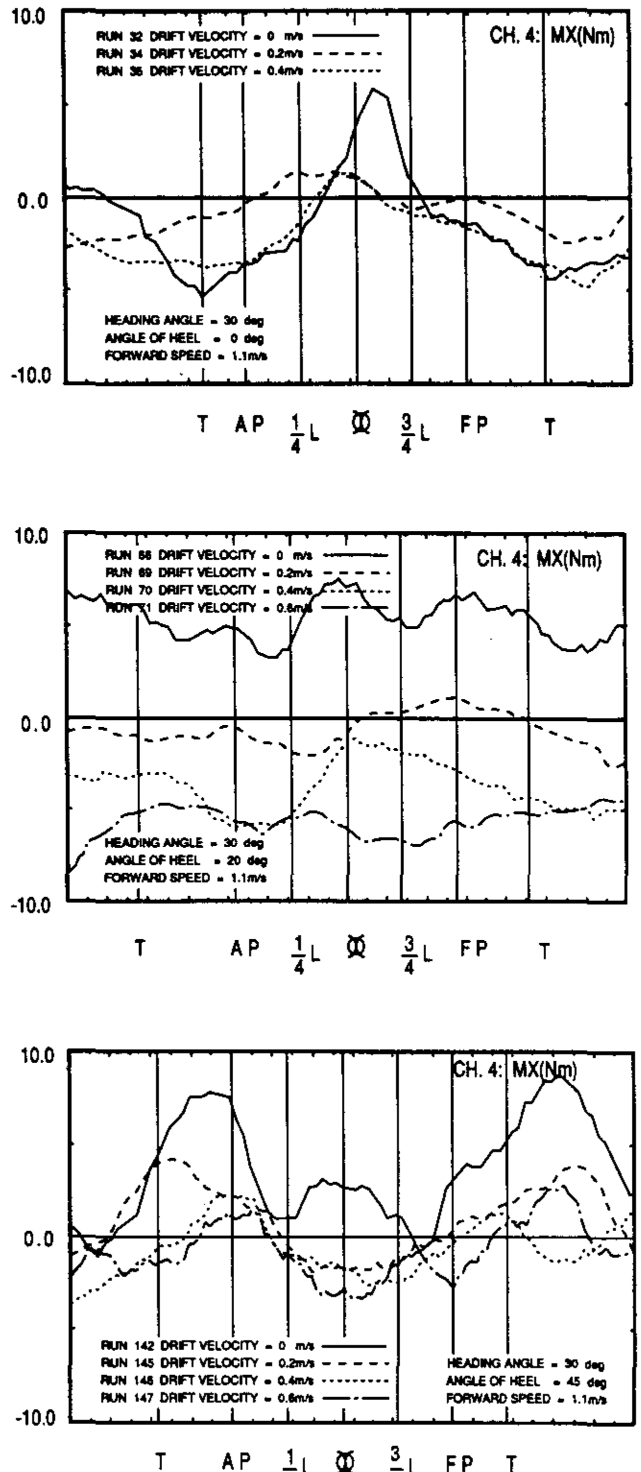


Fig. 23 Influence of lateral motion and bulwark submergence on roll moment in quartering waves (fully captive model)

As the restraints in the vertical motions of the model strongly influence the pattern of the hydrodynamics forces, the same sort of experiments was repeated in the partly captive tests.

An example of a set of the test results for the model running with a medium speed in quartering waves (μ = 30 deg), with the fixed heel angle of 20 deg toward the lee side, is shown in Fig. 24.

The four components of the hydrodynamic force and the heave and pitch motions are presented as the functions of the wave crest position relative to the model. The results of the measurements for the run without any lateral motion are collated with corresponding results for various drift velocities, and are matched with the position of the wave crest. For all these runs the bulwark at the lee side is submerged when the wave crest is passing along the model length. It can be seen that the lateral movement

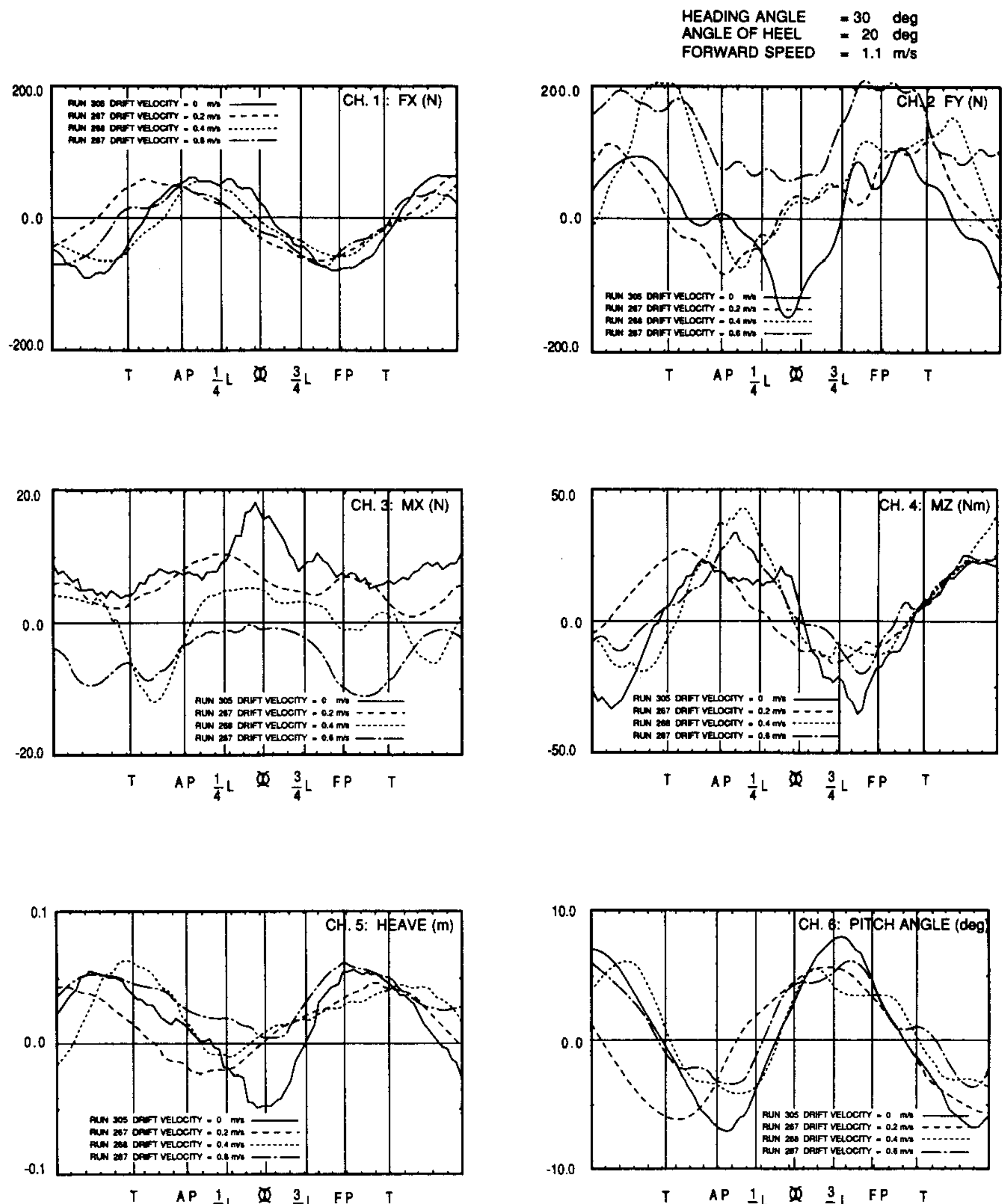


Fig. 24 Influence of lateral motion on hydrodynamic forces and motions generated in partly captive test with model running in quartering waves with a leeward heel $\phi = 20$ deg

toward the lee side affects mostly the sway force (F_y) and the roll moment (M_x).

Alteration of the M_x characteristic for two different heel angles is demonstrated in Fig. 25. At the heel of 45 deg, the bulwark at the lee side is permanently deeply submerged.

The graphs clearly demonstrate the large reduction of the restoring features of the roll moment and indicate that, at a certain velocity of the lateral motion, the roll moment may become a permanent heeling moment (negative moment on the graphs), independent of the position of the wave crest.

The captive model tests confirmed that the lateral motions, combined with the bulwark submergence, create a hydrodynamic phenomenon which generates additional heeling moments and local restraints in the hull motions. The restraints cause some couplings between the lateral motions, heave, and roll, which further enhance the dangerous effects of bulwark submergence.

Analysis of the elements of the model motions presented in Figs. 10 and 11 indicates that the characteristic composition of the motions of a ship moving in extreme quartering waves is conducive to the occurrence of the dangerous effects of bulwark submergence. The impact of a breaking quartering wave on the stern causes a dynamic leeward lateral motion of the afterbody, coinciding with a leeward heel. If the bulwark at the lee side submerges, further lateral motion and heave will generate the previously discussed effects.

Some selected fragments of the records of the free-running model tests provide more evidence of the influence of the phenomenon on ship behavior and display the conditions in which it may occur. In order to facilitate the analyses, the time histories of the motions are presented in the form of one set, together with the record of water level oscillations on the lee side at the midships. The records of the acting waves are included as well.

The time points which correspond to the selected positions of a wave crest relative to the model are marked as vertical lines and each analyzed wave action is clearly indicated at the bottom of the set.

The lateral motion of the local submerged part of the deck is composed of sway and yaw motions. Therefore, these two motions and the heave are taken into detailed consideration in order to detect when the additional heeling moment may be generated.

At the bottom of the time history of each analyzed motion, a thick horizontal line indicates the time when the leeward bulwark is immersed in the water. The shadowed part of this line represents the time when the bulwark is deeply submerged. These time periods are established from the record of the lee side relative motion.

The additional hydrodynamic couplings and heeling moments appear when the local lateral motion takes place from the weather to the lee side, and the bulwark / deck edge at this part of the hull is submerged. The time interval during which this condition is satisfied are marked on the upper part of the sway and yaw time records in the form of thick horizontal lines.

The heave will contribute to the heeling effects, if the movement is upward at the time when the bulwark is submerged and the lateral motion proceeds toward the lee side. The time at which the heave motion is directed upward while the bulwark at the lee side is submerged is marked by the horizontal lines on the heave time records.

All these time-indicating lines are then collated on the record of the roll motion.

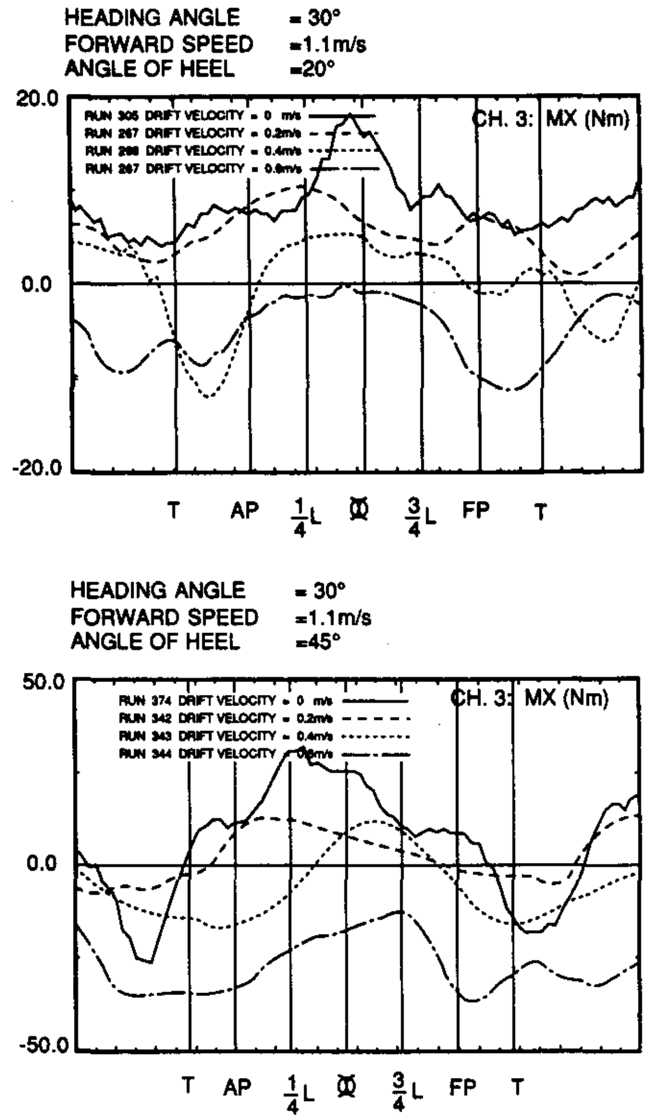


Fig. 25 Influence of bulwark submergence and lateral motion on roll moment in quartering waves (partly captive model)

Figure 26 presents a fragment of a run at the light load condition with the formally sufficient stability curve (condition I / A). The model survived the action of all shorter, extremely steep / breaking waves at this loading condition, despite the large dynamic motions, broaching, and difficulties with keeping the course. In the presented run, the model was advancing with the nominal speed 1.1 m / s in quartering waves, with an average course angle of 30 deg. The nominal parameters of the periodic wave (which was the largest one tested) were: wave period 1.7 sec, wave height 0.65 m.

In the wave trough (T), the model was approximately in a vertical position, and began to roll to the lee side on the front slope of the oncoming wave (wave 1). When the crest of the breaking wave reached the stern, a large impact violently increased the model's motions. Large and fast sway motion toward the lee side, combined with a rapid yaw increasing the course angle, and an upward heave motion took place. If the bulwark on the lee side had not been immersed, the roll motion would have proceeded regularly as shown in Fig. 10, and is marked by the dashed line in Fig. 26.

In the case analyzed, however, the bulwark in the aft part of the hull became submerged shortly after the wave impact (although at midships the bulwark edge was still above the water surface). The additional heeling moment due to sway / yaw and heave motions was generated and the heel angle dramatically increased.

The horizontal dashed lines on the roll graph mark the time when this phenomenon was activated, and the bulwark at the midship was still not submerged.

After the crest of wave 1 passed one quarter of the model length ($L/4$) the roll moment changed its direction and acted as a restoring moment (compare with Figs. 16 and 25). However, the hydrodynamic phenomenon generated on the submerged part of the deck by dynamic sway / yaw and heave were so powerful that they prevented the model from coming back to the vertical position. Instead, the leeward heel increased continuously until one of the elements which generated the additional moments vanished. This took place shortly after the wave crest had passed the model's midships (⊗). The heave motion changed its direction and started to move the model downward. This direction did not enhance the heeling moment, due to heave, and the model reached its maximum leeward heel.

The bulwark was deeply submerged and the model remained subjected to a continuous action of the reaction to the sway and yaw. Shortly after the wave crest had passed midships, the yaw changed its direction and the bow was pushed strongly toward the lee side. At that point, the forebody contributed strongly to the creation of the effects analyzed.

When the wave crest passed the forward perpendicular (FP) the sway reversed its direction and, shortly after this, the yaw lost its momentum. Although the bulwark was still submerged, the additional heeling moment was no longer generated. The model started to recover from the large heel angle due to the roll moment caused by the back slope of wave 1.

Shortly before the position in the next trough (T), the roll motion gained large angular velocity. Although the bulwark was still submerged, and the direction of heave on the slope of the next wave became conducive once again, the lack of lateral motion caused the hydrodynamic couplings not to appear, and the model continued to roll quickly toward the vertical position. This fragment shows that the additional influence of heave appears only in the presence of the lateral motions.

In the middle of the front slope of the next wave (between T and AP of wave 2) the dynamics of the recovering motion were counterbalanced by the heeling moment induced by wave 2. The model started to roll slowly back toward the lee side. Meantime, the bulwark emerged and, therefore, contrary to the action of wave 1, no conditions existed for the creation of the hydrodynamic effects in question.

Thus, when the wave approached midships, the model followed the direction of the M_x moment, that is, started to roll toward the upright position. Though for the time of the wave crest passage between ⊗ and $3/4\ L$ the bulwark edge was exceeded for a while by the wave crest, it was still not a real submergence. Furthermore, the conducive sway motion had too low velocity, and there was no yawing during this period. In effect, the dangerous coupling was not generated by the second wave, and the model came to the vertical position when the crest of wave 2 passed the FP.

The model was not as successful during the next test when running in the same waves, but with greater forward speed.

The nominal speed of the run, which is presented in Fig. 27, was $v = 1.4$ m / s. The first of the analyzed waves (wave 1) met the model at a small heel (about 10 deg) to weather side, running with the course almost zero (about +25 deg on the yaw record), that is, in a following wave position.

As a result of a strong wave impact on the stern, the model moved rapidly forward (see the surge and forward speed graphs) without changes in course, and practically in the upright position. Due to the increase in model speed, the wave crest advanced very slowly relative to the model, and when the crest reached midships the model rode on the crest for longer than one half of a second. The bulwark edge became immersed, and very small sway and yaw caused a slow heeling toward the lee side. However, these factors disappeared very shortly and though the bulwark was submerged, the lack of sway, yaw, and heave motions at the crest position between ⊗ and FP eliminated the possibility of inducing any additional moments attributable to bulwark submergence.

The heel increased to about 35 deg due to a reduction of the restoring moment on the wave crest, but when the crest advanced to about $3/4\ L$ the model followed the direction of the roll moment (which now acted toward the weather side) and started to recover. In the trough, the model resumed a vertical position, but further roll to the weather side was counterbalanced by the heeling moment due to the front slope of the next wave (wave 2).

The model started to roll back to the lee side so that at the moment of the next crest impact, the heel angle reached about 35 deg, and the bulwark was submerged. As a result of the strong impact of the wave crest, the sway and yaw were directed so that they caused the deck edge to plough under the water and generated all the accompanying hydrodynamic effects explained previously. The direction of the heave was also conducive to the induction of the additional coupling.

Because of this, the roll motion did not proceed according to the anticipated characteristic, which is marked by the dashed line on the roll graph. Rather, the leeward heel increased to 53 deg. When the wave crest was between $1/4\ L$ and ⊗, the heave coupling disappeared but sway / yaw action restrained the bulwark / deck edge from an upward movement and the model could not roll back, despite the restoring action of the wave slope after the crest had passed midships. The model remained in a heeled position (about 45 deg), and even before the model got into the next trough, it began to roll farther to the lee side, forced by the effects of yaw motion and the direction of the acting roll moment (compare the moment M_x for the heel angle 45 deg in Fig. 25). The direction of yaw motion was changed and the course angle, which was coming back to 30 deg (0 line in the yaw graph), began to increase, turning the model toward the beam position with respect to the wave.

As on the front slope of the next wave (wave 3) the yaw / sway and heave motions generated the hydrodynamic effects on the submerged part of deck, the heel angle further increased, and when the wave crest hit the side (WS), the model capsized upside down in the beam position to the wave. The capsize event was marked by the symbol © on the roll angle record (Fig. 27).

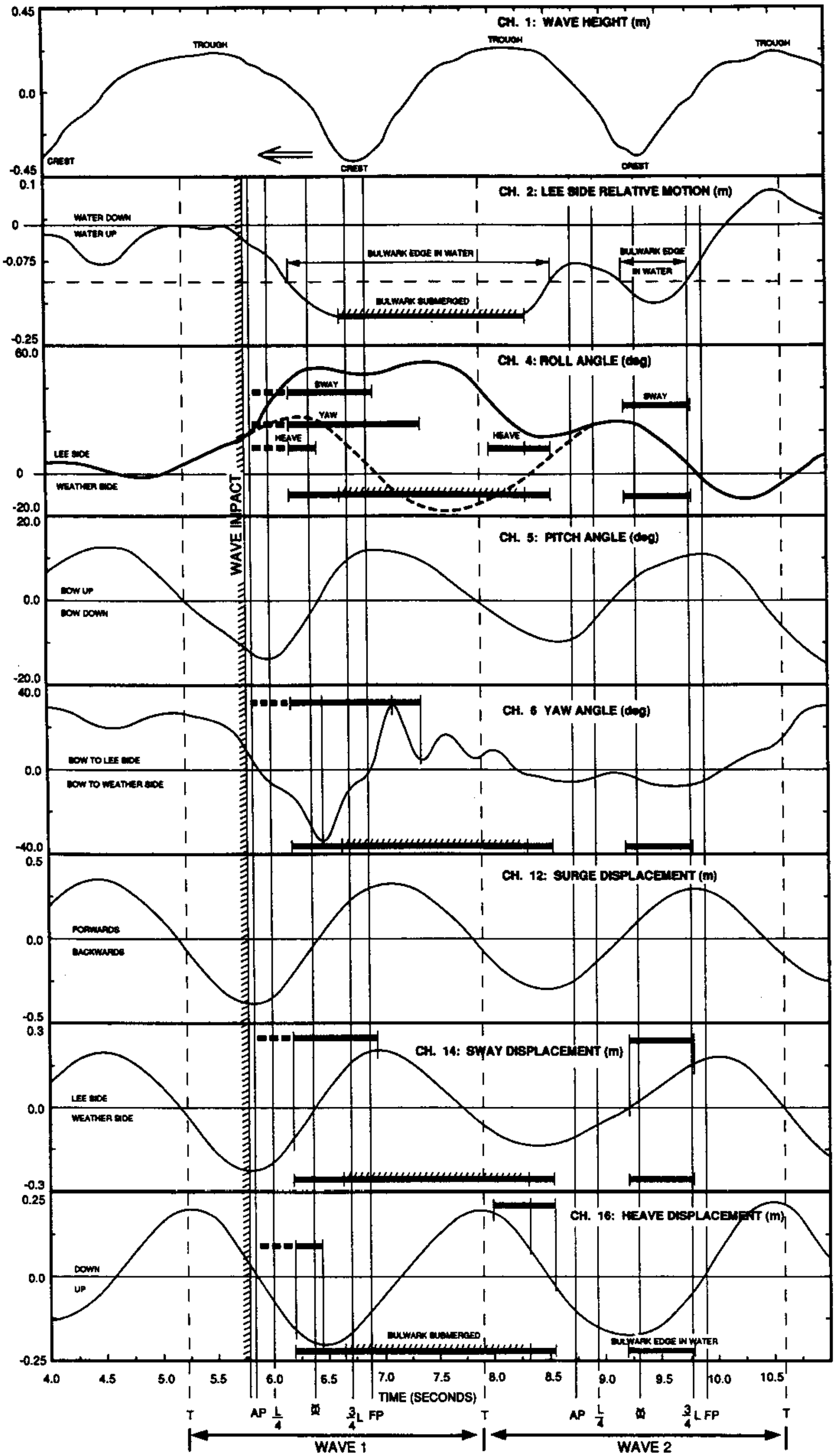


Fig. 26 Influence of hydrodynamic phenomenon created by bulwark submergence on roll motion—fragment of time record of a free model's run in breaking quartering waves; free running test No. 25; load condition I/A; nominal forward speed v = 1.1 m/s; heading angle μ = 30 deg; nominal parameters of periodic waves: H = 0.65 m, T = 1.7 sec

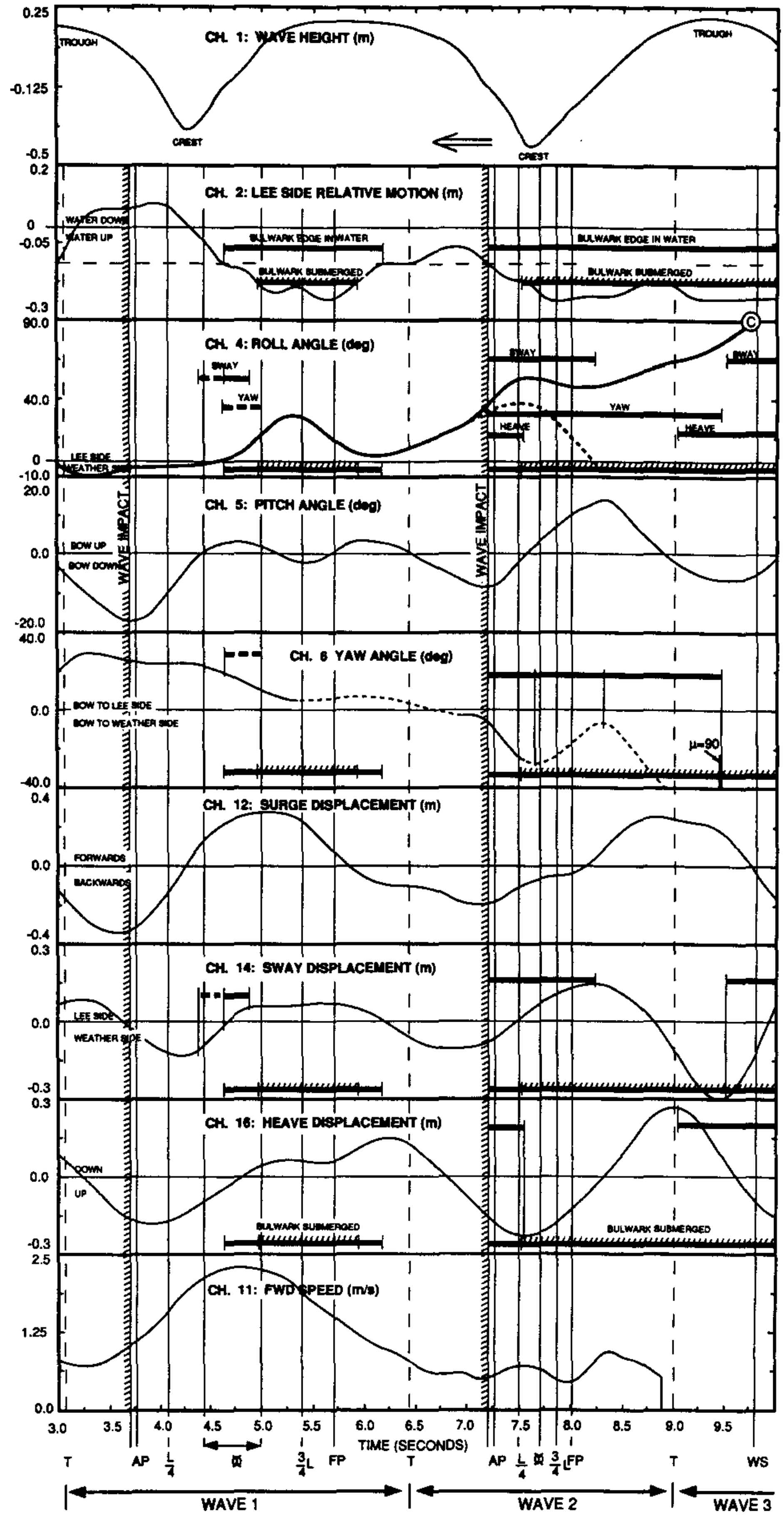


Fig. 27 Time history of model capsize in breaking quartering waves; free running test No. 27; load condition I/A; nominal model speed v = 1.4 m/s; course angle μ = 30 deg; Periodic waves with nominal parameters: H = 0.65 m, T = 1.7 sec

Evidently, the hydrodynamic effects created by the deck edge ploughing under the water were the major factors that brought the model to capsize.

In all other runs at this loading condition, where the analyzed phenomenon either did not appear, or lasted only for very short period, the model moved safely in the waves.

The set of time records presented in Fig. 28 constitutes an example of the model behavior and capsize at the light load condition with the stability curve which does not satisfy the IMO stability criteria (condition I / B—Fig. 8). At this loading condition, the model survived the testing in smaller waves, but capsized in all waves with nominal height to model depth ratio $h / D \geq 1.4$.

In the test presented in Fig. 28, the model ran with a nominal speed $v = 1.4$ m / s in periodical waves with the nominal parameters: wave height $h = 0.38$ m, wave period $T = 1.3$ sec.

At the beginning of the run (wave 1), the model performed the characteristic pattern of motions in quartering waves, similar to those described in Section 6. Wave 2 met the model in a position perpendicular to the wave crest (following waves position). The model was then pushed forward by the wave crest, and rode for some time on the crest with a very slow change of course, without roll, maintaining a small weatherward heel angle. Although some sway motion appeared in the leeward direction, no coupling effects were created because the bulwark was, at all times, above the water surface. The next wave (wave 3) increased the course angle and, at the moment when the wave impact on the stern occurred, the model was in a quartering position with the course angle $\mu \sim 30$ deg.

Unlike during the previous capsize, the model motion was not affected by the bulwark submergence during the first phase after the impact of wave 3. When the wave crest got close to midships, the bulwark became submerged, and the sway / yaw motion activated the deck edge ploughing effects. As a result, instead of rolling back, the model was kept at the inclined position during the movement on the back slope of the wave. The next wave (wave 4) further inclined the model. As the bulwark was submerged at all times, the forced yaw / sway and heave motions activated the additional heeling mechanism. The model was turned back from its course of $\mu \sim 70$ deg and, at the moment of the impact of wave 4, the course angle was about 35 deg.

Because of the deep submergence of the bulwark, the wave impact did not change the direction of yaw, and the model turned farther toward a following waves position. Shortly after the impact, the model capsized on the wave crest upside down, in a position perpendicular to the wave crest.

In both capsize events analyzed (Figs. 27 and 28), the heeling mechanism generated by the submerged bulwark / deck edge and the appropriate direction of the lateral motions, and sometimes the heave, was clearly evident and constituted the major cause of the model's capsize.

Stability reduction on a wave crest

The reduction of a stability curve when a ship is moving on a wave crest is usually considered to be one of the major threats to the safety of the ship.

The record of the run presented in Fig. 29 may be considered an example in which this effect contributed to the capsize of the model. The test was carried out for the light load condition with poor stability (condition I / B), as in the previously analyzed case. This time, however, the model ran with a low forward speed ($v \sim 0.7$ m / s). The nominal wave parameters were: wave height $H = 0.50$ m, wave period $T = 1.5$ sec.

As the model speed was low and the heading angle about 40 deg, the first wave (wave 1 in Fig. 29) passed the model length fairly quickly.

As a result of its action, the model heeled to about 30 deg leeward, and some water shipped on the deck through the stern ramp and above the bulwark on the weather side at the beginning of the wave action. When the wave crest was passing FP, the bulwark at the lee side immersed, and the lateral motion of the forebody, caused by the yaw motion on the back slope of the wave, generated the effect of local restraint of the bulwark motion. This prevented the model from rolling to the vertical position..

The next wave (wave 2) met the model running with a course of about 15 deg, that is, close to the "following wave" position. The sharp, breaking wave hit the heeled model at the stern, pushing it forward. Some water got on the deck through the ramp. After the wave crest passed $L / 4$, the model speed was close to the speed of wave propagation and, as a result, the model started riding on a very sharp wave crest. The angle of heel increased from an initial value of 15 deg to about 30 deg, and the leeward bulwark became submerged again. The angle of heel increased as the sway motion enhanced the heeling moment. The model was inclined to 40 deg when the crest was close to FP.

The results of the captive tests indicate that for these heading and heel angles, the moment M_x begins to act as a heeling moment after the wave crest passes $3 / 4\ L$. In effect, the model rolled farther toward the lee side on the back slope of wave 2. In the next wave trough, it was already heeled more than 60 deg and started to turn to the "following wave" position.

The heel angle was increasing on the front slope of the next wave (wave 3) and was further enhanced by the same coupling effects caused by yaw and heave.

The model capsized on the crest of wave 3 at the position approximately perpendicular to the crest (at the last phase it even crossed the zero course line, so that the lee side became the weather side).

The critical moment in this run appeared to be the riding of the model in a heeled position with the small heading angle (close to a vertical position to the wave crest) on a very sharp, steep crest of wave 2.

It seems that the large increase of the heel angle from 15 to about 40 deg during the model ride on the crest can be attributed primarily to the reduction of the restoring capability on the wave crest in the presence of a heeling moment induced by some amount of water accumulated on the deck at the lee side and enhanced by the sway action.

Loss of stability due to water on deck

Shipping and accumulation of green water on deck is widely recognized as one of the most dangerous elements affecting stability safety. This is particularly true in the case of small vessels, where the mass of the water trapped in the deck well may constitute a significant percentage of the ship's displacement.

The experiments with the model in the light load conditions I / A and I / B did not expose water accumulation on the deck as the cause of capsizing. The larger freeboard and the large responsiveness to wave actions prevented the deck from a systematic overflooding through the stern ramp and over the weather side bulwark. If some amount

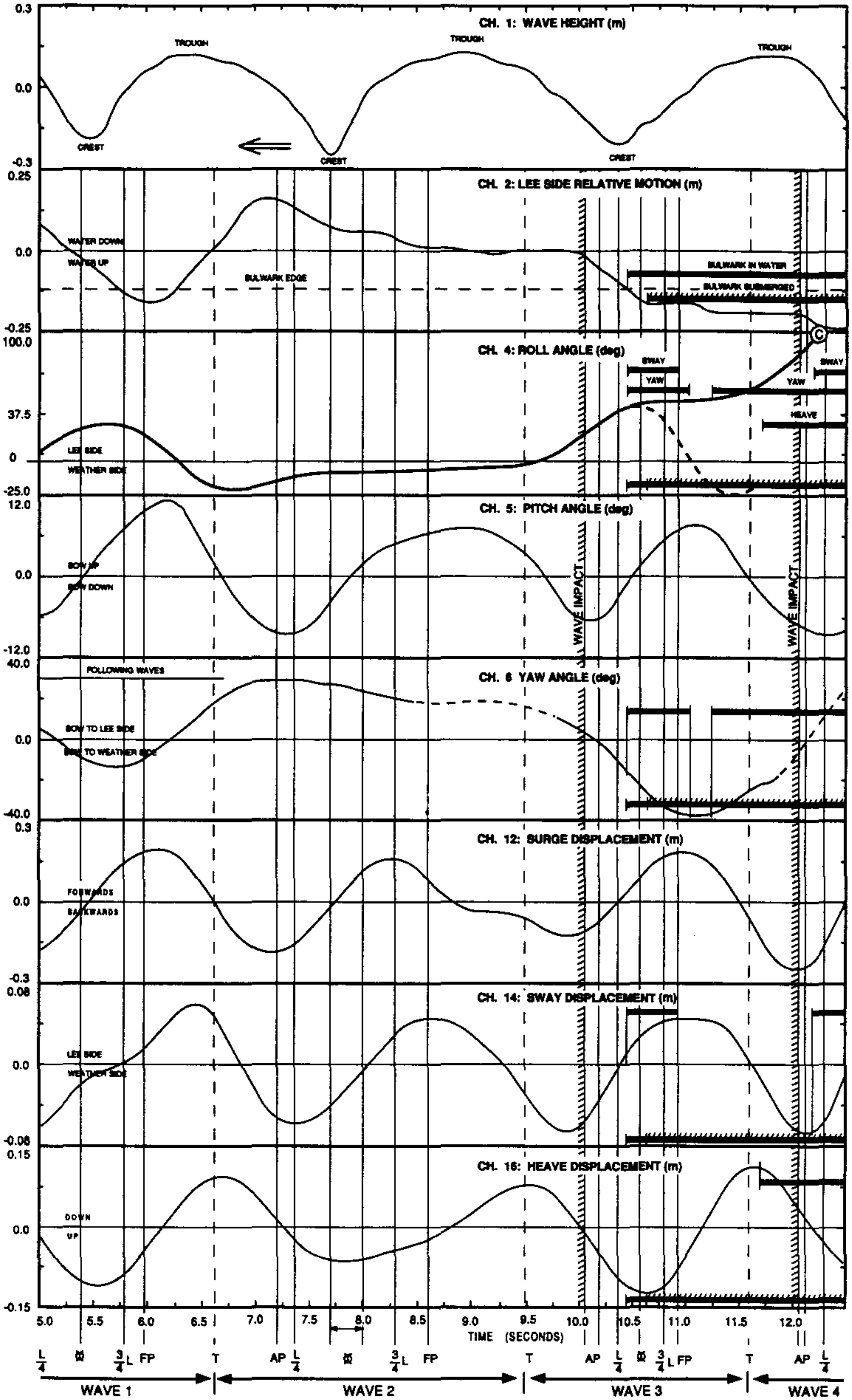


Fig. 28 Time record of capsizing of model with poor stability; free-running model test No. 54; loading condition I/B; nominal model speed v = 1.4 m/s; effective speed V_R = 0.85 m/s; nominal course μ = 30 deg; periodic waves with nominal parameters: H = 0.38 m, T = 1.3 sec

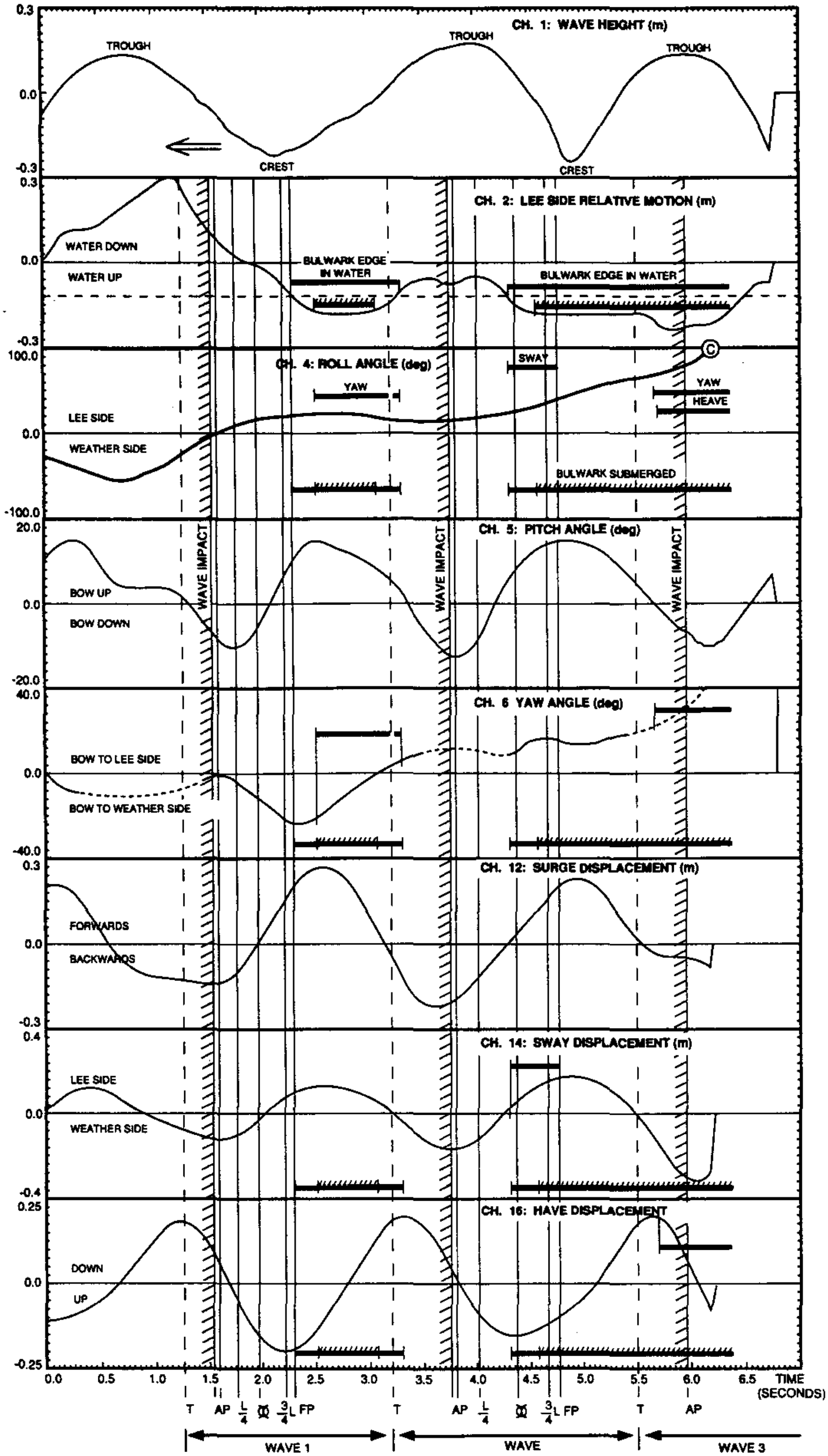


Fig. 29 Model capsize caused by stability reduction on a wave crest; free-running test No. 60; load condition I/B; forward speed v = 0.7 m/s, nominal heading angle μ = 30 deg; nominal parameters of periodic waves: H = 0.50 m, T = 1.5 sec

of water accumulated on the deck, it dispersed before the next wave action.

An immersion of the bulwark at the lee side, which was analyzed earlier, should not be confused with the effects caused by the water trapped on deck. The phenomena which occur when the bulwark at the lee side is submerged are a result of the hydrodynamic reactions of the surrounding water to the motions of the submerged part of the deck and the bulwark, while the effects caused by water trapped on the deck are of an inertial nature, attributable to the mass of water.

The model tests carried out for full load conditions II / A and II / B provide evidence of the dangerous influence of the water on deck on the ship's resistance to capsize.

Unlike at the light load condition, the dynamics of model motions are much smaller at the full load condition, and the freeboard height is very small. This facilitates water shipping on deck through the stern and above the bulwark at the weather side.

The water shipped and accumulated on deck in many tests and, in particular during runs with low forward speed. The wave frequency encountered at small forward speed was such that the water trapped on deck did not manage to dissipate before another amount of water was delivered by the next wave, and the mass of water was increasing.

A fragment of a time record in Fig. 30 is a good example of a ship's behavior with a systematically increasing mass of water on deck. The test was performed in irregular waves at a significant wave height $H_{1/3} = 0.36$ m and modal period $T_m = 1.7$ sec.

The model, ballasted to condition II / A, that is, full load with a poor stability curve (Fig. 9), was advancing with slow forward speed $v = 0.6$ m / s at the nominal heading angle $\mu = 30$ deg. As a result of the first wave action, the model accumulated some water on deck and was heeled leeward to an angle of about 15 deg. At the beginning of the time record fragment (Fig. 30), the model rolled around a leeward angle $\simeq$ 15 to 17 deg, and the heading angle was reduced to about 5 deg.

After the impact of large wave 1, the sway and yaw motions were conducive to the generation of the additional heeling moment, but the bulwark at the lee side was not immersed. The increase of the heel angle was caused by the heeling moment due to the wave acting at the increasing heading angle, and by an additional mass of water on deck which was brought by the wave.

The bulwark became fully submerged when the crest of wave 1 passed 3 / 4 L, but the lateral motion at that time practically vanished. After the first wave passed, the angle of heel decreased slightly from 29 to 25 deg, but the bulwark remained submerged.

The next wave did not exert an impact and the forced lateral motions were small, without any significant dynamics. Furthermore, the phase of heave was such that the upward motion occurred when there was no effective leeward lateral motion. In effect, no significant additional coupling effects due to bulwark submergence were generated during the action of waves 1 and 2.

However, the mass of the accumulated water on deck as well as the heel angle was increased. The heading angle started to decrease systematically due to the submergence of the bulwark at the lee side. The water on deck and the submerged bulwark prevented the model from rolling back to the vertical position. Although the subsequent waves were very small, and did not create large heeling moments on the model, which was running almost following the waves (heading angle $\approx$ 5 to 10 deg), they further increased the amount of water on deck. As a result, the heel angle was systematically increasing and the model finally capsized in a position perpendicular to the crest of wave 5.

The systematic shipping and accumulation of water on the deck of the model with poor stability was the major cause of this capsizing.

In most cases, the model at the II / A condition was brought to capsize not by a single cause, but by a combination of a number of elements which formed unfavorable conditions when the model was moving in breaking quartering waves.

An example of such a combination is presented in Fig. 31, where the model was running with an average speed $v = 0.65$ m / s in irregular waves with $H_{1/3} = 0.30$ m and $T_m = 1.5$ sec. The heading angle varied between 20 and 0 deg (following waves) due to frequent submergence of the bulwark on the lee side.

As a result of an impact of a big breaker (wave 2), a large amount of water came on deck and, simultaneously, the model was heeled toward the lee side. The heel angle was enhanced by the additional moment caused by the sway and yaw with the submerged bulwark, and the water on deck accumulated at the lee side. When the crest of wave 2 passed the bow, the water on deck and the resistance to the motion of the submerged bulwark / deck edge prevented the model from rolling back to the upright position.

The next wave (wave 3) repeated the same action, but on the hull already inclined to about 25 deg leeward, and with much stronger coupling effects generated by the bulwark / deck edge submergence. More water shipped on the deck as well. After the wave passed, the submerged bulwark and the water on deck once again prevented the model from recovering.

Although the next wave (wave 4) was relatively small, it did not give any chance for the model, which was already heeled to over 50 deg, to recover. The combination of the heeling moments discussed earlier and the vanishing of the restoring potential brought the model to ultimate capsize on the crest of wave 4.

9. Role of operational conditions in ship capsizing

The analyses of the free-running model tests provided a great deal of important information on the influence of various factors on ship susceptibility to capsizing in quartering waves. They confirmed the importance of some traditionally recognized elements and put some other factors in a new perspective.

In the previous section, some specific physical phenomena generated by the hull-waves interaction were analyzed. The danger created by bulwark submergence, by the reduction of the ship restoring capability on a wave crest, and by the accumulation of water on deck were demonstrated and discussed.

Two events, which were observed at various time during the testing, and which are considered by some authorities as specific autonomous phenomena, were not discussed separately—namely, broaching and ship riding on a wave crest. Both are attributed to ship movement in the following waves. If the model, which was running at high speed in following waves, did not lose course control after wave impact on the stern, a wave riding occurred. If it lost course control, it started to broach.

The two phenomena do not constitute a direct cause of

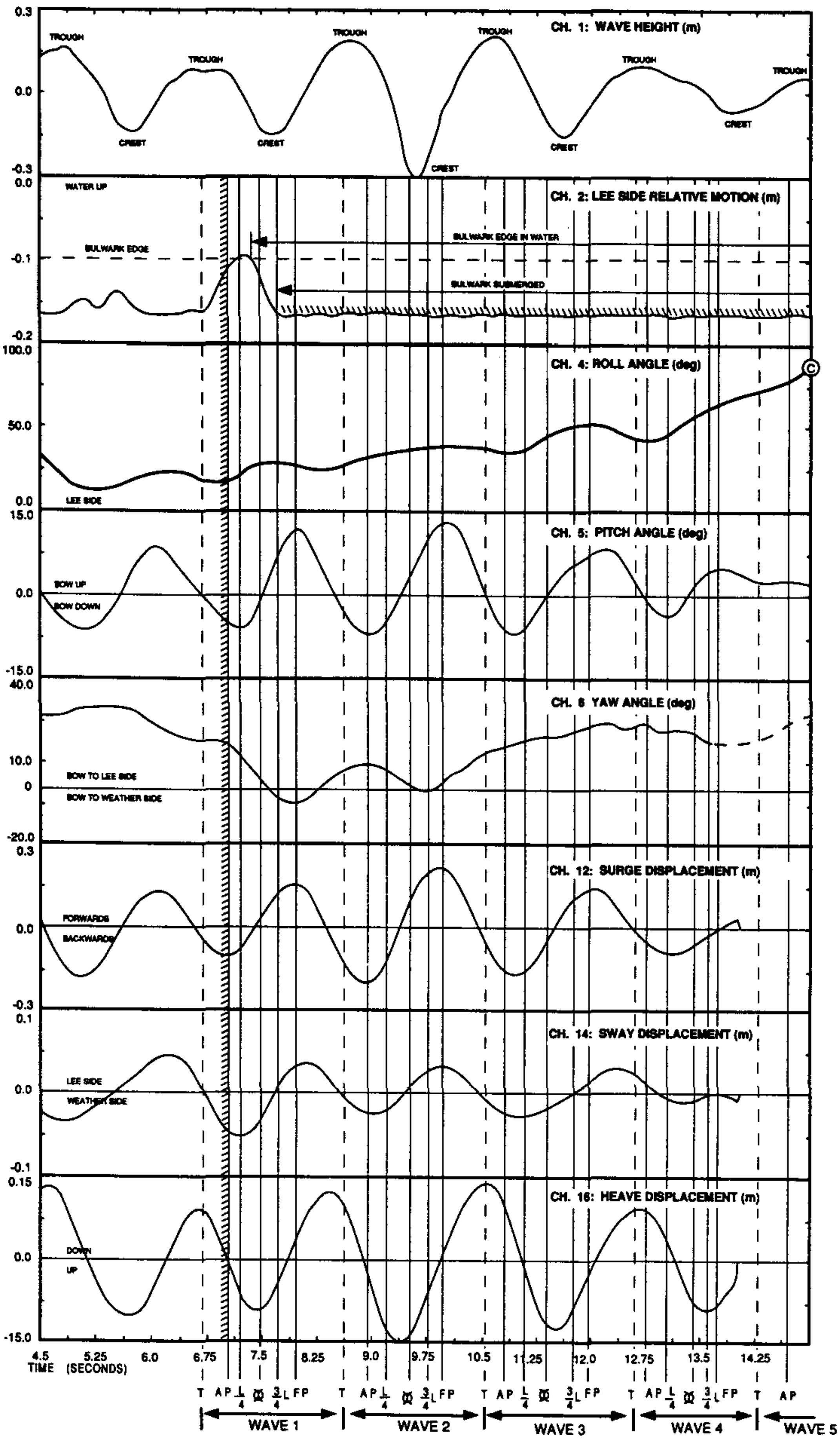


Fig. 30 Model capsize due to water on deck in irregular quartering waves; free model test No. 99, loading condition II/A, forward speed v = 0.7 m/s; nominal heading angle μ = 30 deg; JONSWAP spectrum, $H_{1/3}$ = 0.36 m, T_m = 1.7 sec, γ = 3.3

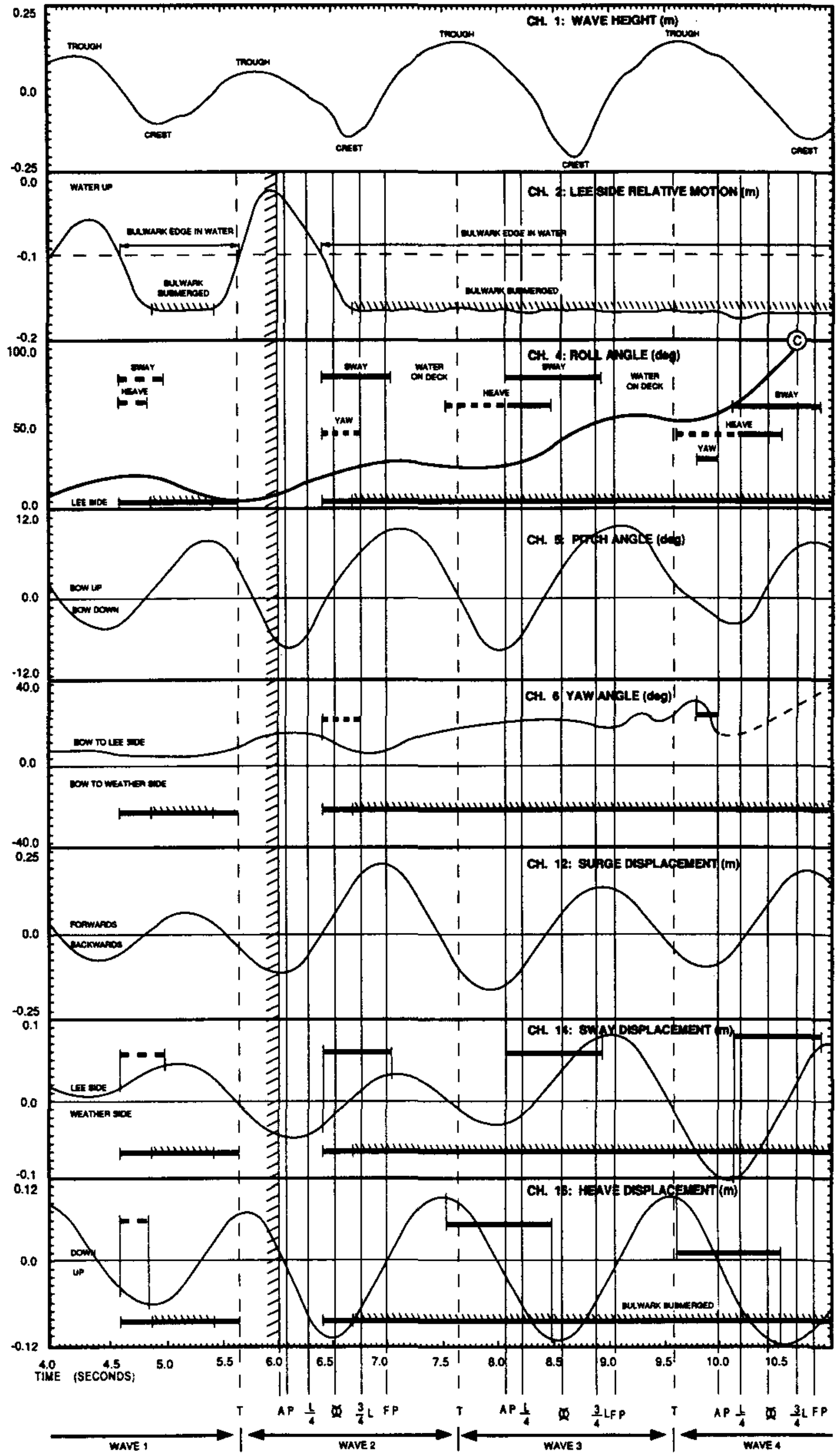


Fig. 31 Model capsize due to combination of bulwark submergence and water on deck in irregular quartering waves; test No. 86; loading condition II/A; model speed v = 0.7 m/s; nominal heading angle μ = 30 deg; JONSWAP spectrum; γ = 3.3, $H_{1/3}$ = 0.30 m, T_m = 1.5 sec

capsize, but do activate certain mechanisms which have already been discussed.

By causing a ship to remain on a wave crest for a relatively long time, the riding phenomenon facilitates the reduction of the restoring capability on the wave crest. If, at the same time, any heeling moment acts on the ship, the situation ends either with a large heel angle (see Fig. 27—wave 1) or with a capsize (Fig. 29—wave 2).

The loss of course control and broaching induce a dynamic yaw motion and leeward heel, which essentially constitutes the same behavior as after an impact of a quartering wave. The only difference consists in a higher initial forward speed and acceleration (because of the following wave position) and subsequently larger yaw rate. The high yaw rate with the large forward speed creates centrifugal moments which increase the leeward heel angle.

The dangerous situation created by broaching (together with the wave action) consists in dynamically bringing the ship to a large angle of heel which, in the case of bulwark submergence, generates the previously discussed coupling effects.

The influence of some factors which reflect the operating conditions is highlighted in the following.

Righting arm curve

The tests confirmed that the ship behavior in extreme waves is correlated with the shape and values of the *GZ* curve. Despite large motions, the model ran successfully at both load conditions when the *GZ* curve was satisfactory (that is, I / A and II / B). Only the highest tested waves brought the model to capsize at the light condition I / A. Contrary to this, at the conditions which were characterized by the insufficient stability curve (conditions I / B and II / A), the model survived operations only in the smaller tested waves and became susceptible to capsize at the medium wave heights. Although the mechanisms of capsizing were different in both cases, the propensity to capsize was similar.

In fact, it is difficult to discuss the *GZ* curve for a ship moving in oblique seas. The restoring moment which is represented by this curve does not exist during motions in oblique waves. The real moment, M_x, acting on a ship is a resultant hydrodynamic moment corresponding to the hull-wave interaction, and even the hydrostatic part of this moment for a transient configuration of the immersed body in a wave would not have the same meaning as the hydrostatic restoring moment in calm water. However, the consistency of the results proves that the righting arm curve reflects the ship's capability to withstand the waves' action and could be considered as one of the factors representing stability safety in general.

Load condition

Significant differences in the model's behavior in waves were observed at the two load conditions tested.

At the light condition, the model was more responsive to wave actions. The motions were very dynamic and with large amplitudes. A greater tendency to riding on wave crests and to broaching was noticed. The heeling mechanism created by the bulwark submergence was mostly involved in model capsizing.

At the full load, the hull was positioned deep in the water and the resistance to lateral motions as well as the inertia effects were much larger than in the light condition case. The motions were smaller and less dynamic. Less tendency to broaching and crest riding occurred. Water on deck was the dominating factor in the majority of the capsizes.

Course angle

The heading angle relative to the main direction of wave propagation strongly affects the behavior of ships in waves. In quartering waves, at a heading angle 10 to 30 deg, a strong influence of large surge motion on the dynamics of other motions can be observed. The increase of forward speed due to wave impacts, which occurs frequently at small heading angles, enhances the probability of broaching or wave riding and increases the magnitude of these phenomena if they occur.

At the heading angles $\mu > 40$ deg, amplitudes of the lateral motions and of roll are much larger than at the smaller heading angles. The large motions are caused directly by the wave exciting forces and not by broaching.

Running in following waves did not induce dangerous roll unless any additional heeling moment was occurring (see Fig. 27—wave 1 and Fig. 28—wave 2).

The experiments in beam waves confirmed that this course does not constitute the most dangerous situation. The tests with the model at the full load (low freeboard) and low stability (condition II / A) were carried out in regular beam waves with the nominal parameters $H = 0.44$ m, $T = 1.4$ sec.

With these parameters, the model capsized at each run when moving in quartering waves at each forward speed tested. However, it operated safely when running beam to the same waves. Also, no danger of capsize occurred during tests in beam irregular waves, while the model almost always capsized when it was running in the same waves at quartering courses.

An explanation of this surprising fact can be found in Figs. 12 and 13. Although the roll, heave and sway motions display large speed and fairly large amplitudes, the phase lags between themselves and relative to the wave profile prevent the ship from an intensive shipping of water at the weather side and from the ploughing-under effect at the lee side.

The tests proved that the most dangerous situations arise when the ship is moving in quartering waves. It seems that the most hazardous course lies in the range of heading angles of 15 to 45 deg.

Wave parameters

The degree of danger which impends over a ship exposed to wave action depends on two wave characteristics: wave steepness and wave height relative to ship size.

Extremely steep and breaking waves generate the most dynamic course of the induced phenomena, while wave height stimulates the magnitude of energy applied on a hull. Obviously, the magnitude of energy necessary to capsize a ship depends on the size of that ship. Thus, the wave height to ship depth ratio may be one of the indicators of the potential threat created by the waves.

No essential difference between the model behavior in periodic waves and in a sequence of comparable irregular waves was observed, if at least three or four large waves constituted the train of irregular waves. On this basis it is advantageous to carry out the capsizing model tests in periodic waves, because it is difficult to synchronize a model run with the development and propagation of irregular waves so that the model could meet a required sequence of extreme waves.

Forward speed

Forward speed plays an important role in the ship's behavior in extreme waves. However, its influence on ship propensity to capsize is different for different load conditions.

In light load conditions, the greater speed enhances large ship motions, facilitates the occurrence and enlarges the negative effects of broaching and bulwark submergence and, thus, significantly increases the probability of capsizing.

At full load, when the hull motions are smaller and water on deck constitutes the main cause of capsizing, the higher speed prevents a ship from intense water shipping on deck (in particular, through the stern) and increases a chance for ship survival. At the full load condition II / A, the model capsized many times when running with a low or moderate speed, but survived despite large motions and difficulties with course-keeping when running in the same waves but with a high forward speed.

Initial conditions

The model tests have demonstrated an essential influence of the initial conditions at the moment of wave impact on the subsequent history of ship motion and, thus, on a probability of ship capsizing in waves.

The position of a hull in space, the direction and the velocity of the motions, as well as their composition at the moment of wave impact, decide the ship's response to a wave action. Examples of this influence can be found in Figs. 26, 27 (compare the model position and the direction of motions at the moment of impact of waves 1 and 2) and in Fig. 28 (compare the initial conditions and the results of actions of waves 2 and 3).

For this reason, any numerical simulation of ship behavior in extreme waves has to be exercised for a wide range of the parameters characterizing the initial conditions, unless the most dangerous combination of the initial conditions is known.

It is worth noting that usually the action of two subsequent large, extremely steep or breaking waves was necessary to capsize the model with a low yet not entirely inadequate stability curve, at the light load condition. The first wave heels the ship to a large angle, so that the bulwark gets submerged and usually restrained in its motion, and the second wave, acting on a hull with the reduced potential restoring energy, forces the ship to heel further and to capsize.

If the reason for loss of stability is water accumulating on deck, the capsizing process may last longer, and more than two subsequent waves may be necessary to bring the ship to an upside-down position.

10. Concluding remarks

The results of the model tests reported herein demonstrate the applicability of the presented concept of experimental investigation into the mechanism of ship capsizing in waves. The compatibility of the captive test results with the corresponding results of the free model tests confirms that the assumptions of the approach are correct.

Although the elimination of some modes of motion affects the hydrodynamic scattering effects, the partly captive tests provide an adequate qualitative representation of the hydrodynamic forces which are exerted on a ship during its motion and capsizing in extremely steep / breaking quartering waves.

The discrepancy between the forces which are measured in the partly captive tests and the total hydrodynamic forces exerted on a free-running model can be evaluated by appropriate forced oscillation tests in waves.

On the basis of the foregoing analyses of the test results, it is believed that the effects of the restraints introduced in the partly captive tests are small in comparison with the magnitude of the forces generated on the hull by extreme and breaking waves, and in comparison with the major effects caused by a change of the fixed position of the hull (that is, the adjusted heel and heading angles, and the forward and drift velocities). Therefore, the forces obtained by interpolation between the results of partly captive tests for various "frozen" positions may constitute a reasonable approximation of the total hydrodynamic forces acting on a free-running model. Thus, it is possible to evaluate quantitatively the total hydrodynamic forces exerted on a ship advancing in oblique, extremely large, and breaking waves, for which the theoretical (numerical) approaches still fail. The appropriate combination of the correlated free and partly captive tests provides a possibility of the reconstruction of the composition of the hydrodynamic forces which act during ship capsizing and thus a better understanding of the capsize mechanism may be gained.

The proposed experimental approach also constitutes a very good basis for the verification of time-domain simulation programs, not only with respect to ship motions in extreme waves but also with the generated hydrodynamic forces.

The detailed analysis of the experimental results confirmed the important influence of some of the factors traditionally considered, such as righting arms curve and wave parameters, on ship stability safety, and shed some new light on the influence of other factors.

However, the most valuable and direct effect achieved by application of the experimental approach developed is the identification of the hydrodynamic phenomena created by bulwark and deck edge submergence. If the bulwark at the lee side becomes submerged when the ship moves in steep waves, the lateral motions of the hull induce local restraints to the motions of the submerged part of the deck and of the bulwark. These restraints cause a shift of the longitudinal axis of rotation to the vicinity of the deck edge and create a pivot-like effect. The new hydrodynamic couplings between roll, sway, yaw, and heave are activated and the additional heeling moment is generated. The stiffness of the local restraint and the magnitude of the generated additional heeling moment depend, first of all, on the lateral relative velocities and on the size of the immersed part of the deck.

This phenomenon requires further study, in particular with respect to the quantitative influence on the total roll moment and to its mathematical representation.

It must be emphasized that the phenomenon discussed has a hydrodynamic nature and is generated by the reaction of the surrounding water to the movement of the submerged part of the deck. It should not be confused with the effects of water trapped on deck, which are of static and inertial nature.

The experiments demonstrate that the effects created by bulwark submergence may dramatically increase a ship's susceptibility to capsizing, and may cause a capsizing of a vessel which, according to the existing stability criteria, may be considered safe.

The tests also confirmed that the most dangerous situations are created when the ship moves in quartering waves. Some phenomena which are characteristic for operation in quartering waves never occur in beam or following waves. They also cannot be obtained by a superposition of the hydrodynamic effects which appear in these two separate cases. This means that the stability level which could be achieved by the separate studies of ship behavior in beam and in following waves would not provide sufficient safety for a ship operating in quartering seas. Therefore, ship movement in extremely steep / breaking quartering waves, and the hydrodynamic phenomena generated at this course, should be considered as a basis for the establishment of future stability safety requirements.

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