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SUMMARY

A revealed dangerous hydrodynamic phenomenon generated on the submerged part of the deck and bulwark when a ship operates in quartering, extreme waves is presented in details. Examples of model experiments where this phenomenon was evident and was a decisive factor in the ultimate capsize are presented. The magnitude of the heeling moment is discussed and preliminary results of the mathematical model of the hydrodynamic effects developed are presented.

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EFFECT OF BULWARK AND DECK EDGE SUBMERGENCE IN DYNAMICS OF SHIP CAPSIZING

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Stefan Grochowalski graduated from the Technical University of Gdansk, Poland, in 1966 as M.Sc. - Naval Architect. He received the Doctor of Technical Science degree with specialization in Naval Hydrodynamics in 1976, at the same University. He worked at the Ship Research Institute of the Technical University of Gdansk since 1966 until 1981, as Asst. Professor and carrying out research in the field of ship dynamics in waves, ship resistance and propulsion. Author of the method and formulae for determining the "protecting" freeboard of fishing vessels, adopted by the Torremolinos Convention 1977. In 1981-83 visiting scientist at Institut für Schiffbau der Universität Hamburg, Germany, working on ship capsizing problems. Since 1983-to present, works at the National Research Council, Canada carrying out research in ship capsizing and ship manoeuvrability.
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ABSTRACT

A comprehensive experimental study of the mechanism of ship capsizing in heavy seas has been carried out at the Institute for Marine Dynamics of the National Research Council of Canada. One of the findings was the dangerous hydrodynamic phenomenon created by bulwark and deck edge submergence during dynamic motions of a ship in steep quartering waves. The additional force and heeling moment which may be generated, influence strongly the dynamics of a ship in waves and significantly increase the likelihood of ship capsize.

The paper discusses the nature of the phenomenon, explains its influence on ship motions, and presents the examples of model experiments where this influence was evident and was a decisive factor in the ultimate capsize. The magnitude of the generated heeling moment and the conditions when it can occur, are discussed.

Preliminary results of calculations carried out using a newly developed mathematical model of the hydrodynamic effects on the submerged deck are presented and discussed. They provide a good explanation of the abnormal roll motion of the model, when bulwark submergence occurs. The difference between the cases "water on deck" and "deck in water" is explained and the direction of further necessary research is outlined. The current practices in evaluating

stability safety are discussed and the inadequacies are pointed out.

INTRODUCTION

Stability safety in heavy seas still constitutes an unsolved problem for many types of ships. The complex physical nature of the capsize phenomenon and large number of possible scenarios are the main reasons for this situation. Development of rational stability standards or operational guidelines for avoidance of capsize in extreme conditions, cannot be achieved without full knowledge of the mechanism which brings a ship to capsize. A mathematical model, which has yet to be developed, must represent adequately the complex dynamics of a ship in extreme waves for a general, most complicated case. This was the reason that the research program of ship capsizing being carried on at the Institute for Marine Dynamics of the National Research Council of Canada, was focused in its first phase on the study of the mechanism which causes ship capsize in quartering, extremely steep and breaking waves.

The program contains theoretical studies, model testing and development of mathematical models. As the experiment data are considered to be the main source of information on complex physics of capsize phenomenon and at the same time, the best base for a validation of theoretical formulations, the model testing was specially designed in order to provide this necessary data.

According to the philosophy developed, the model test program consisted of:

1) Free-running tests - with the objective of investigating the dynamics of motions and capsizing at various loading conditions, various breaking waves and forward speeds;

2) Captive tests (fully and partly captive) - with the objective of identifying the hydrodynamic forces exerted on a ship by extremely steep and breaking waves for various wave directions, forward speeds, heel angles and drift velocities.

In order to provide the possibility of reconstructing the capsizing mechanism, the free-running and captive model tests were correlated so that for any instantaneous position of the model with respect to the wave profile in the free-running situation, the appropriate situation in the captive tests could be found and as a result, the composition of the hydrodynamic forces can be interpolated. This was made possible by use of video-recording in which the time counter was synchronized with the time base of the main data acquisition system.

A model of a typical small Canadian hard-chine stern trawler of 18.6 m length was used in the experimental studies. As many as

440 runs were performed. The results were recorded in the form of time histories of motion components or hydrodynamic forces, and in the form of video-records.

The philosophy of the experimental approach, the test technique developed, and the program of experiments performed have been presented in (Grochowalski, et al., 1986). Some results of the analysis of the kinematics and dynamics of ship motions in quartering breaking waves, as well as analysis of various types of capsizing have been reported in (Grochowalski 1989).

Although the experiments were performed with the model of a small fishing vessel, the adopted methodology and the results provide insight into the mechanism of capsizing process and the findings have a more general sense. They can be applied to other classes of ships.

Detailed analysis of the model test data is still being continued. However, the results achieved so far, shed some light into the complicated nature of ship capsizing in heavy seas. One of the most interesting findings of the experimental study is a hydrodynamic phenomenon generated when the bulwark and part of the deck become submerged during dynamic motions of a ship in quartering, breaking waves. This phenomenon changes ship dynamics in waves and can bring to capsizing a vessel which, according to the existing criteria, may be considered as a safe one. First analyses of the effects of bulwark and deck edge submergence were reported in (Grochowalski, 1989 and 1990).

The paper presents further analysis and explanation of the hydrodynamic effects, provides some results of theoretical calculations, and discusses problems which have to be solved in order to include these effects into stability evaluation.

HYDRODYNAMIC PHENOMENON GENERATED BY BULWARK AND DECK EDGE SUBMERGENCE

The nature of the effects on the submerged deck

When a ship is moving in quartering waves she performs a very characteristic composition of motions. A detailed analysis of this composition has been presented in (Grochowalski 1989, and 1990).

The characteristic sequence of motions when the wave crest is passing along the hull, between the stern and the bow, is very unfavourable from the capsizing point of view. The following three phases of the cycle seem to be critical:

- After a wave impact on the stern, the ship is dynamically pushed forward and aside (leewards) and acquires a large leeward heel. The stern is pushed to lee side causing dynamic yaw. Advancing of the wave crest toward the midships increases further the forward speed and leeward sway, while roll continues to increase the heel angle to the lee side. As a result, a large part of the deck edge at the lee side is moving down and attains a large lateral velocity leewards.

- Maximum heel angle is reached when the ship is on the wave crest, which increases the likelihood that the bulwark gets submerged while the restoring capability is significantly reduced. Surge or riding on the wave crest causes that this situation is maintained for a relatively long time.

- When the wave crest is at the forebody the direction of yaw, surge, and roll is reversing, and now the bow is being pushed towards the lee side and upwards, while the leeward heel angle may still be large.

A characteristic element of these three phases is that during that time at least part of the lee-side bulwark is in a very low position and moves leewards. This facilitates bulwark submergence.

If the bulwark becomes submerged, and at the same time, that part of the hull executes lateral motion towards the immersed side (see: Fig.1), the submerged part of the deck is being forced to plough under the water. The resulting pressure on the submerged surface generates a hydrodynamic resistance to the motion. The reaction R of the surrounding water has such a direction that it creates an additional roll moment M_{XD}, which tends to increase the heel angle. If as a result, the heel increases, the additional heeling moment increases as well, enhancing the dangerous mechanism.

The hydrodynamic effects on the submerged part of the deck are of a dynamic nature. The reaction R is generated only if there is a movement of the submerged elements in relation to the contiguous water. Furthermore, the direction of the relative movement of water particles must be "in" the element of deck surface. Otherwise, the interaction of water with the elements of deck is purely static and is included in traditional calculations of stability. The normal components of the inflow velocities (see Fig.1) generate dynamic pressure on the deck surface, while the tangential ones create a tangent reaction which is of viscous nature. Viscous effects are also generated at the submerged edge of the bulwark. In addition to the hydrodynamic effects caused by relative velocities, the lateral motion of the submerged part of deck towards the immersed edge causes inflow of additional mass of water into the deck space. This mass constitutes and additional load which enhances the reaction R significantly, and increases the additional heeling moment M_{XD}.

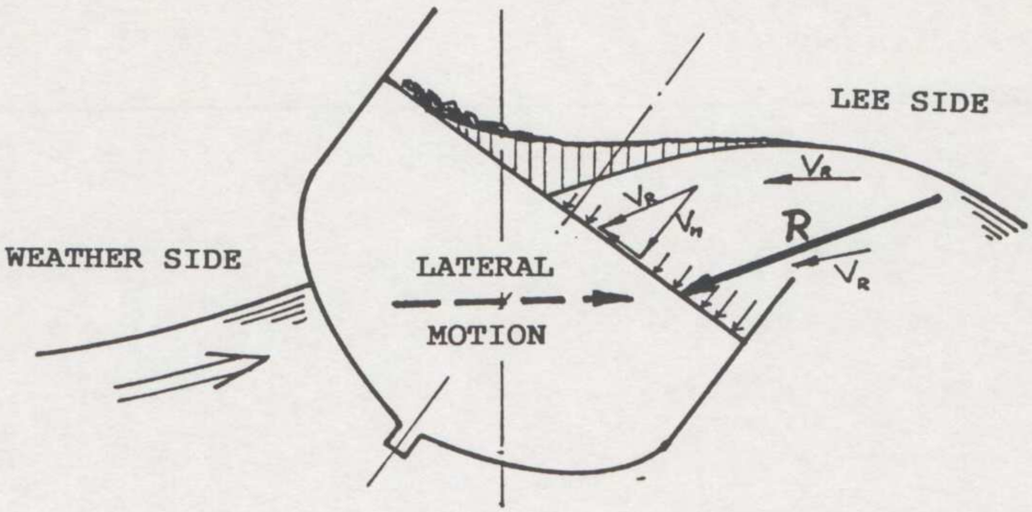

Fig.1 Hydrodynamic effects generated on the submerged deck in waves

These general considerations, together with the model tests results reported in (Grochowalski, 1989), indicate that it is the lateral motion of the submerged part of the deck which constitutes the main factor in the generation of the additional heeling moment. The lateral motion, which is composed of sway and yaw, creates the inflow relative velocities which subsequently generate the dynamic pressure on the submerged surface, and also increase the load on the deck due to the mass of water above the deck.

The vertical components of ship motion (heave and pitch) may also contribute in generating the relative velocities of water directed "in" the elements of deck surface, but that influence is not significant if there is no lateral motion. In the case of pure roll, the effect of movement of the submerged deck and bulwark appears in a form of increase of roll damping. The contribution of heave and pitch in the creation of the additional heeling moment may become very important if the vertical movement of the submerged part is directed up at the same time when the conducive lateral motion occurs (Fig.2).

The hydrodynamic effects created by the underwater ploughing movement prevent the bulwark and deck edge from coming out of the water. This causes local restraints to the hull motion. The stiffness of this restraint depends, first of all, on the lateral relative velocities of the surrounding water, and on the size of the immersed part of the deck. If, simultaneously with a fast lateral motion and bulwark submergence, the ship is forced by the wave to heave up, the restrained deck edge causes the hull to turn about a longitudinal axis located close to the bulwark, and a pivot-like effect occurs. This creates a strong coupling between roll, lateral motion, and heave, increasing strongly the heeling moment (Fig.2).

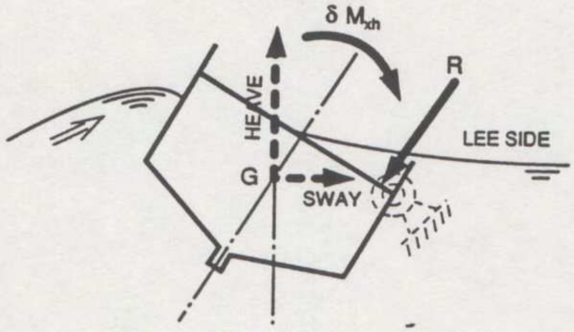

Fig.2 Pivot-like effect caused by bulwark submergence, lateral motion and heave

The restraint of the motion of the submerged bulwark 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.3) 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^*. It can be seen that only a significantly smaller wave can be counterbalanced by the ship in this configuration.

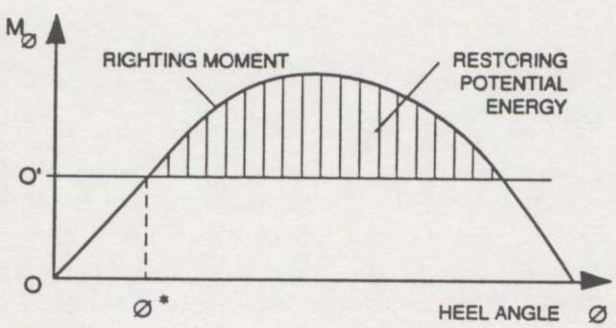

Fig.3 Reducing effect of bulwark submergence on ship potential restoring energy

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. In effect, the leeward heel angle increases further, threatening the ship with capsize. This is why in the model tests in quartering waves, usually it is a second wave which causes the ultimate capsize.

Evidence of the effects of bulwark submergence in the model test results.

In order to investigate the effects discussed, some of the captive model tests were carried out with a lateral leeward drift and the hydrodynamic forces were measured for various combination of drift velocities and leeward heel angles. The tested situations corresponded to that presented in Fig.1.

The first experiments were performed on calm water with the model moving forward and simultaneously being forced to drift in the same direction as the heel.

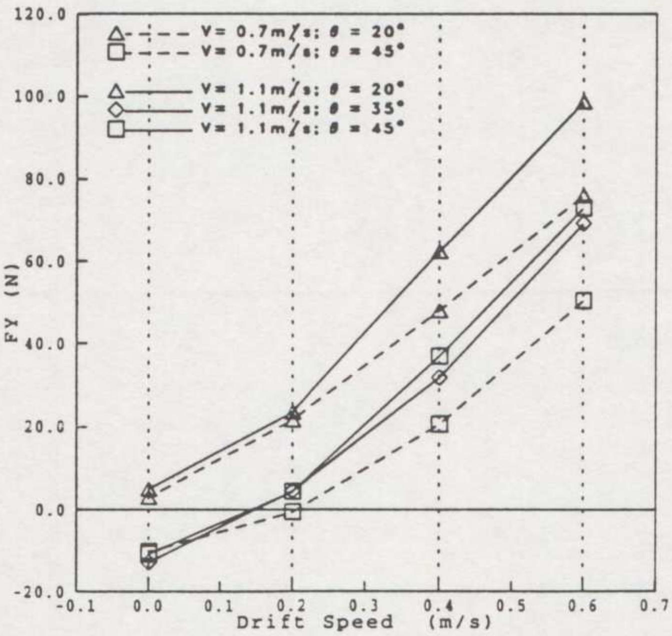

Fig.4 Sway force generated by lateral drift at various heel angles in calm water - captive tests

Fig.4 presents the results of the measurements of the total lateral force. At the heel angle Θ=20 deg. the upper edge of bulwark was still above the water surface, while at Θ=35 deg. and 45 deg., the bulwark was deeply submerged and part of the deck was in water. The measured force is a lateral resistance of the hull and is approximately proportional to square of the drift velocity.

Large portion of this resistance should be attributed to large afterbody skeg. At the large heel angle (35 and 45 deg.) the lateral projected area of the hull is smaller and the influence of the skeg gets very small but now part of the deck is in water and contributes significantly to the lateral force. The dependence of the lateral force on the lateral velocity remains approximately quadratic despite the deck submergence.

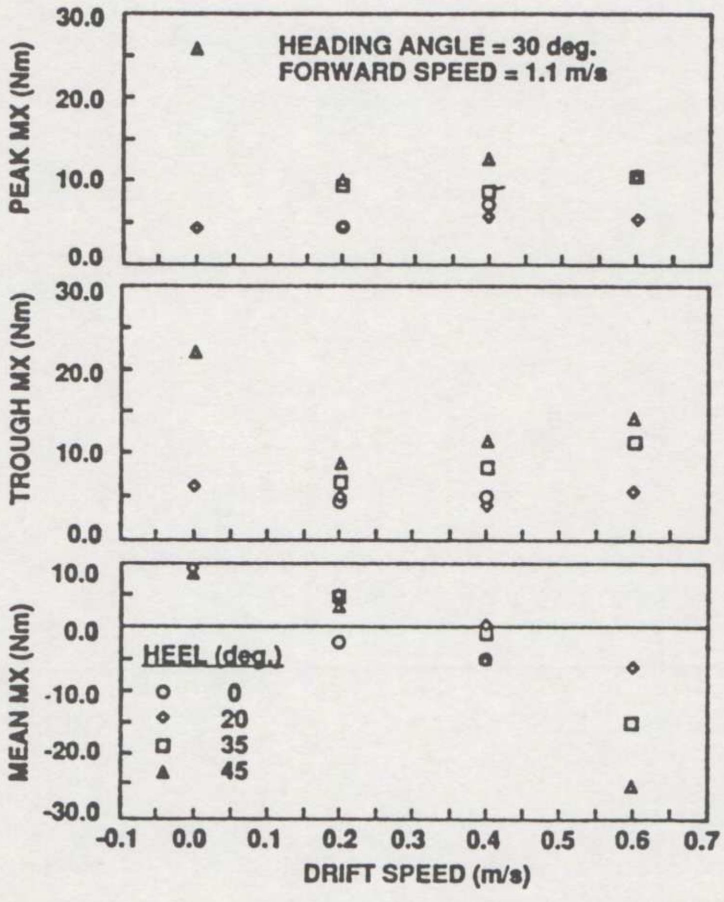

Fig.5 Influence of drift speed on roll moment at heeled position (semi-captive tests, regular waves)

The influence of drift velocity on the total roll moment in waves in the partly-captive tests, where the model was free to heave and pitch, is shown in Fig.5. The moment M_X is presented in the form of mean value and the responses to the action of wave crests and wave troughs (measured with respect to the mean M_X). At the heel of 20 degrees, the bulwark was submerged when the wave crest was between the stern and there quarters of the model length. At the heel of 45 deg. the leeward bulwark was deeply submerged throughout the whole action of the quartering wave. It can be seen that if there is no drift, the mean moment at the tested heel

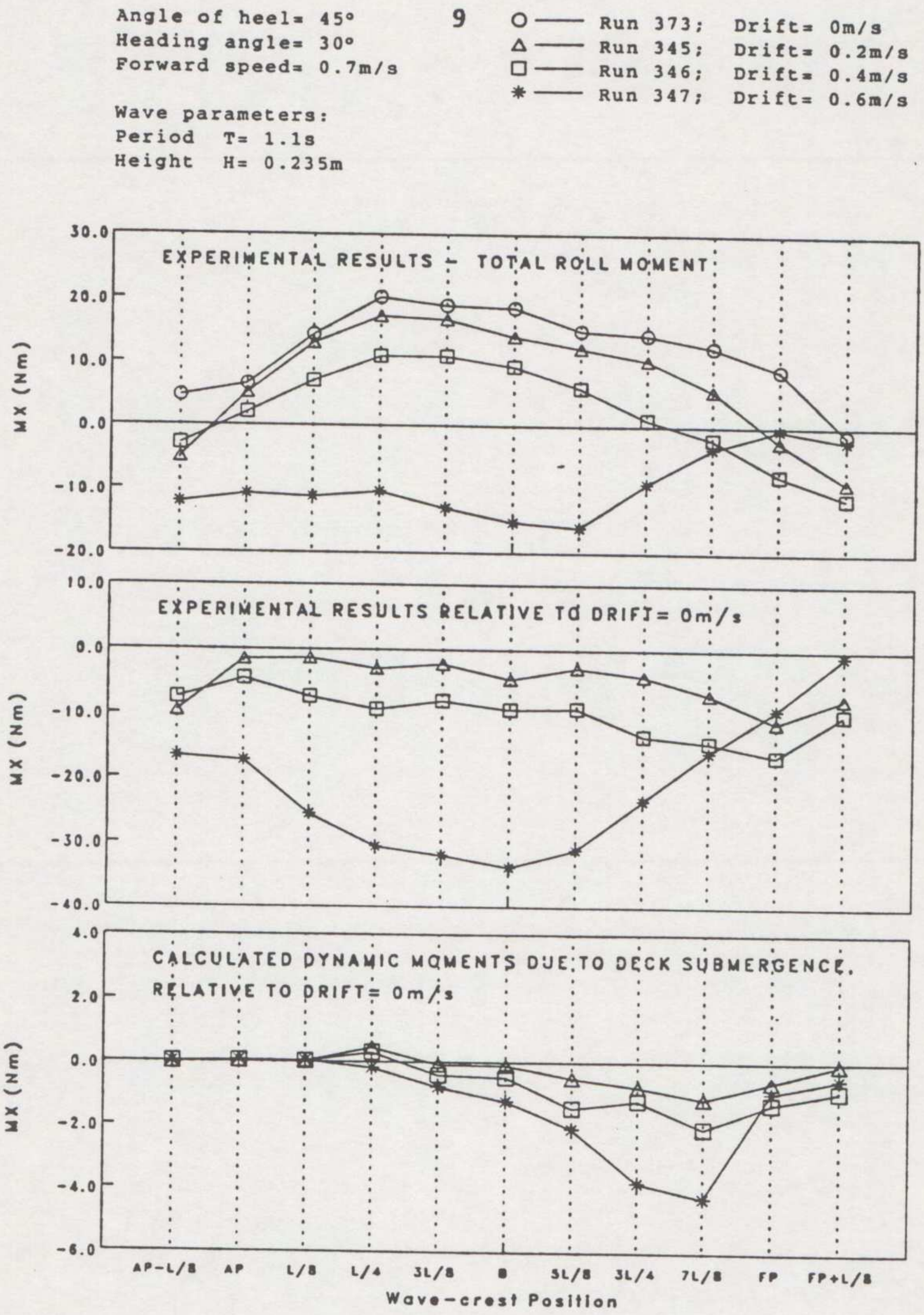

Fig.6 Roll moment generated by lateral drift in waves. Semi-captive model test results and the calculated dynamic moment due to deck submergence.

angles is positive (static restoring moment). When the leeward drift occurs, the mean value of M_x is shifted toward negative values. The larger drift and heel angle, the larger the shift of mean M_x. The change of M_x is very dramatic particularly for larger heel angles, as larger part of the deck remains deeply submerged through a longer time period. For instance, at the heel angle 45 deg. the mean M_x changed form about +8 Nm without drift (restoring moment), to -26 Nm (heeling moment) at the drift velocity 0.6 m/sec! Clearly, the reaction generated on the submerged part of the deck is a major cause of these effects.

Another example of the partly-captive tests is given in Fig.6 (upper and central graphs). The model which was kept at heel of 45 degrees to the lee side and moving forward with the smaller speed in quartering waves, was forced to drift leewards with adjusted velocity. The graphs present the time histories of the moment M_x during the passing of the wave crest along the hull.

The position of the wave crest with respect to the model (AP, 1/8, 1/4...) is marked by vertical lines. It can be seen that in the run without lateral drift, the roll moment is positive for the wave crest positions considered. According to the reference system adopted in the tests, this moment acts opposite to the heel angle, and thus it is a restoring moment. This is caused mainly by the static restoring moment attributed to this heel angle. When leeward drift occurs, the moment is decreasing. The larger the drift velocity, the larger the reduction of the restoring moment. This confirms the generation of an additional heeling moment which counteracts the restoring action of the M_x moment. At a certain velocity of the lateral motion, the roll moment becomes a heeling moment throughout the whole cycle of the wave action.

The central graph of Fig.6 presents the difference between the moments with - and without drift. This difference can be considered as a magnitude of the additional heeling moments generated.

Although the moments measured in the captive tests are the total moments, and the lateral drift changes also pressure on the rest of the immersed part of the hull, the comparison with the runs when the bulwark was not submerged clearly points out on the submerged part of the deck as the main cause of generating such dramatic changes in the roll moment.

The evidence of the discussed phenomenon can also be found in the time histories of the free model runs. Fig.7 (A,B,C) presents a fragment of a run at the light load condition (I/A) with the GZ curve satisfying the IMO criteria. This run was analyzed in details in (Grochowalski 1989, and 1990). The main elements of that analysis are outlined next. The time when the bulwark on the lee side is submerged is marked as a horizontal thick line at the bottom of the graphs. The time points which correspond to some selected positions of the wave crest relative to the model (like aft perpendicular AP, L/4, etc.) are marked as vertical lines and also numbered: (1),(2)....(13).

Graph C presents the time record of roll motion during a little bit more that one cycle of the wave action. In order to analyze the influence of the main contributors in the generation of the heeling moment on the submerged part of the deck, the record of the measured yaw is given in graph A, and sway velocity is presented in graph B. In addition, heave velocity is also given in graph B.

According to the previous considerations, the additional heeling moment will be generated if the lee-side bulwark gets submerged and, at the same time, the submerged part of the deck is in a lateral motion towards the lee side. Heave will contribute to the heeling effects if it is upwards at the same time. The time when these conditions are satisfied is marked by horizontal lines on graphs A and B. The dotted line in graph C represents the typical roll motion of the model in this loading and wave conditions when the bulwark does not submerge.

In the wave through the model was approximately in the upright position, and began to roll to the lee side on the front slope of the oncoming wave (see: graph C). After the impact of the wave on the stern (AP - time point (1)), the bulwark at the stern became submerged, although at midships the bulwark edge was still above water. This was found by detailed analysis of the video-records. The characteristic composition of sway, yaw and roll started to generate the additional heeling moment and the heel angle dramatically increased. The roll angle reached its peak when the wave crest was in the region of midships (time (3)). Approximately at that time, heave contribution varnished and yaw changed its direction reducing the influence of the aft part of the submerged deck. The model started rolling back very slowly. But sway direction was still conducive and the contribution of the submerged deck of the forebody was growing due to dynamic motion of the bow towards the lee side. The hydrodynamic effects were enhanced again, and the model started to roll further to lee side. The roll reached its second peak at time point (9), when the wave crest was well in front of the bow, and the model started to recover.

It was not clear at that time why the model did not start to roll back when sway and yaw were no longer conducive (time (6) and (7)). Although yaw was still pretty dynamic, it was the stern and not the bow which was moving leewards, while the wave crest was in front of the bow (time 7.1 seconds to 7.4 seconds).

As the restraining mechanism did not act any longer, after the time point 7.4 sec., the model started to roll back, but on the front slope of the oncoming next wave it was forced to roll again to the lee side. At this time, however, the wave broke before

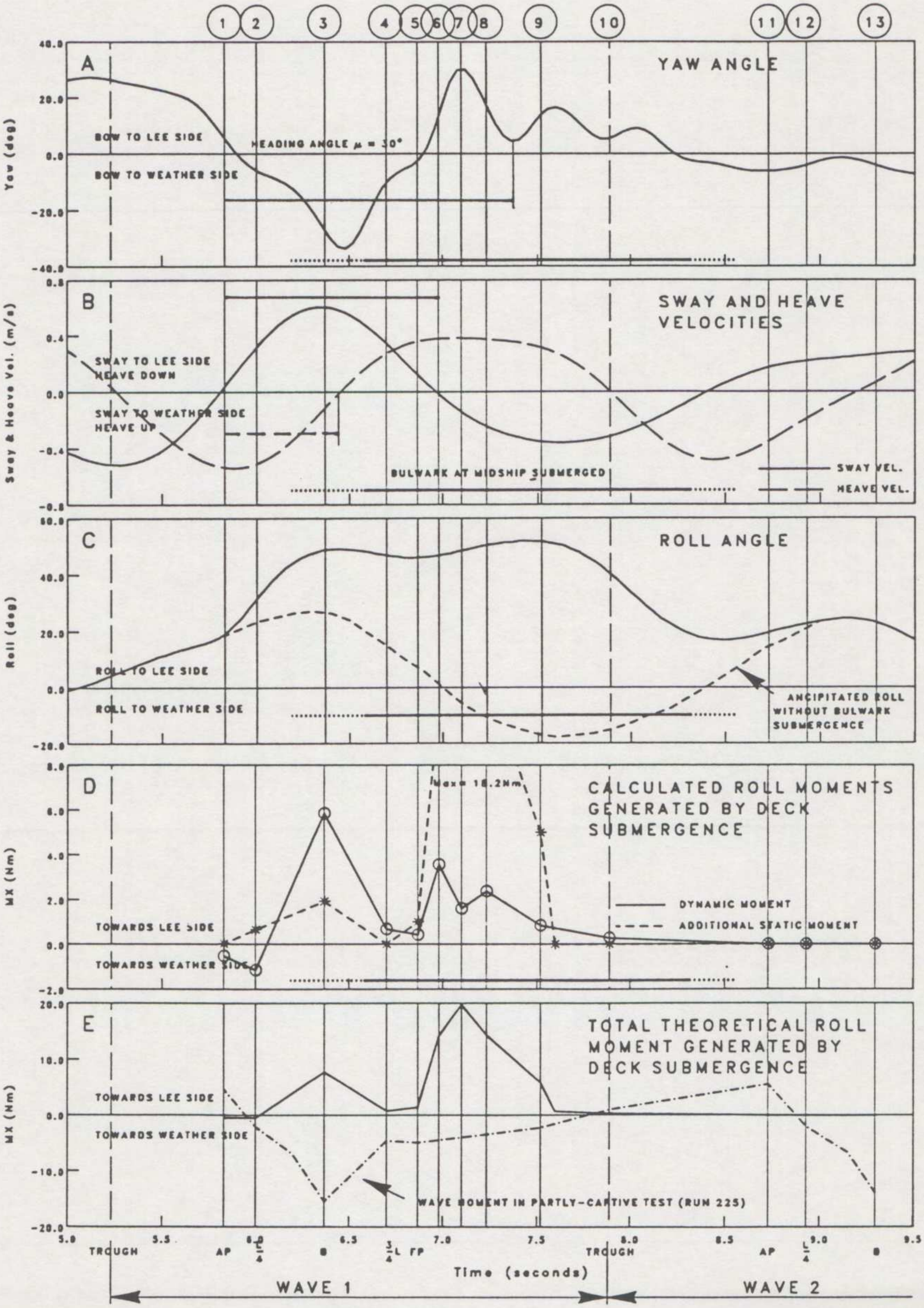

Fig.7 Influence of deck submergence on roll motion. Fragment of time record of the free-model tests No. 25 (graphs A, B and C), and the calculated roll moment generated on the submerged part of the deck (graphs D and E).

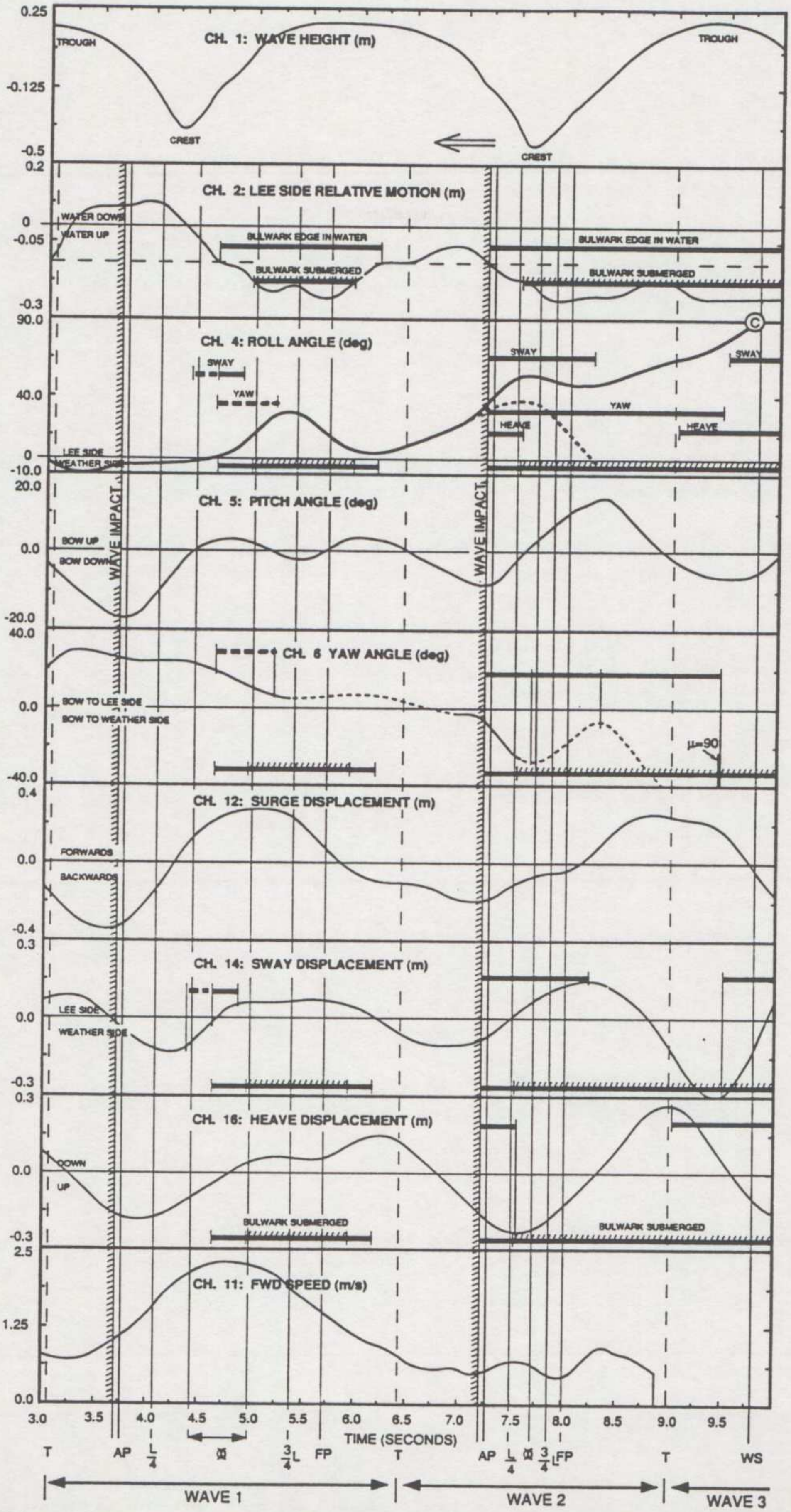

Fig.8 Time history of model capsize caused by bulwark submergence effects. Free model tests. Run 27.

reaching the model, the wave height was smaller, and the bulwark was essentially above water. No additional heeling mechanism was generated, and the model rolled back after the wave crest passed the midships.

The difference between the anticipated roll and the recorded time history in Fig.7 C, is an indication of the dramatic influence of bulwark submergence on ship capability to withstand the action of large quartering waves. How critical that influence can be, it is shown in Fig.8. The loading and wave conditions in that run were the same as in the previous one. However, the forward speed of the model was a little bit larger.

The first wave met the model in the position perpendicular to the crest (see: yaw graph). The wave impact pushed the model forwards without any heeling effects. The model was riding on the wave crest and started to broach a little bit. Although it was heeling to the lee side and the bulwark became submerged, there was no conducive lateral motion and therefore, the additional heeling moment was not generated. The model came to the upright position.

During the action of wave 2, the situation was different and due to sway, yaw and heave the heeling mechanism was created during bulwark submergence and the model remained in deep heel after the first wave passed. The situation during the action of this wave was similar to that presented in Fig.7. However, the next wave (wave 3) was large and steep again, and met the model in a large heel. The generation of the additional heeling moment by the submerged part of the deck during the third wave action was enhanced and heeled the model further. As a result, the model capsized up-side-down.

THEORETICAL PREDICTION OF THE EFFECTS OF BULWARK SUBMERGENCE

Bulwark submergence causes two major physical phenomena: water shipping on deck, and hydrodynamic pressure on the submerged part of the deck and bulwark. Both phenomena could be theoretically estimated if the water flow in the submerged area is defined. However, in the case of ship moving in large waves, the behaviour of water in the submerged deck area is extremely complex. In particular, in the early phase of the process, when the bulwark is not deeply submerged, water flow is disturbed immediately after reaching bulwark edge where mass of water drops down into the deck well. In case of large amount of water on deck, the flow induced by deck movement collides with the external inflow, while the moving boundaries in the form of bulwark complicate the situation even more. Viscous effects on the deck and bulwark, and a dynamic swell-up complement this complicated, dynamic phenomenon. In addition, the character of this event is changing in various phases of submergence.

From the capsizing point of view, the most important situation is when the bulwark gets deeply submerged. The additional heeling moments, presented in the previous chapter, occur mostly when the water surface above the submerged part of the deck is a continuation of the adjacent water surface, and that is when the bulwark is deeply submerged (see: Fig.1).

In order to calculate the hydrodynamic forces on the immersed part of the deck and the bulwark, a mathematical model and a computer program have been developed. It has been assumed that the bulwark is deeply submerged and the forces generated are mainly of the inertial and gravitational nature (i.e. dynamic pressure and additional load). Viscous effects are neglected at this stage.

Calculation of the dynamic pressure on the submerged elements of the deck and bulwark is based on a relative velocities concept. This includes all the components of ship motion and the orbital velocities of wave motion. The deformation of the wave profile and of the wave velocities ,caused by the presence of the hull in the wave, is not considered in the first version. The dynamic pressure is assumed to be proportional to second power of the relative velocities.

The additional mass of water (as marked on Fig.1), shipping or escaping off the deck, is also calculated on the basis of the relative velocities concept. In this model, instantaneous velocities of water above the bulwark are calculated and then integrated in time and along the submerged area of bulwark, yielding the total mass of water, in addition to the mass attributable to the undisturbed wave profile above the deck.

The moment due to dynamic pressure on the deck is called here as "dynamic moment", while the moment caused by the additional mass of water on deck - "additional static moment".

The dynamic moments calculated for the partly captive tests presented in Fig.6 are shown in the lower part of Fig.6. Direct quantitative comparison of the calculated and measured values cannot be made because the measured moments represent the total moments generated on the hull and deck due to drift, while the calculated ones are the moments generated only on the submerged deck and bulwark. It appeared to be impossible to deduce the hydrodynamic forces on the submerged deck from the total forces measured in the captive tests. So, only qualitative comparison can be made at this time. It can be seen that the character of changes of the calculated moment when the drift velocity is changed, is similar to the character of changes of the measured values presented in the central graph of Fig.6. The maximum value of the moments at the smaller drift is reached when the wave crest is close to the bow. At the largest drift velocity, the moment is significantly larger, and the peak is shifted closer to the wave position at the midships.

The mathematical model was then used for detailed reanalysis of the free-model run 25, discussed previously and presented in Fig.7. Calculations of the effects of bulwark submergence were made for the same positions of the wave crest as in previous analysis and using the real instantaneous position of the hull in space. Values of the measured instantaneous velocities in all components of the model motion were used in the calculations, while the acting waves were matched by appropriate second order Stokes waves. For each ship-wave position marked in Fig.7 by points (1) - (13) the bulwark immersion was calculated, and the submerged area of deck was found. Distribution of the dynamic pressure on the submerged surface was computed and by integration, the force and dynamic roll moment were found.

The additional mass of water, which is brought into the deck space by relative movement of the deck with respect to the surrounding water, was also calculated from the distribution of the relative velocities of water above the bulwark edge.

The calculated dynamic roll moment, generated on the submerged part of the deck and bulwark, is presented in Fig.7 D as a solid line, while the additional static moment due to additional mass of water, generated by the relative motions, is shown by the dotted line. The ordinary static moment on the immersed deck is not shown because this effect is calculated normally in the Froude-Krylov forces and is included in the total static stability moment. This moment does not cause the abnormalities of roll presented in Fig.7 C.

Fig.9 presents the visualization of the model motion given in Fig.7 (A,B,C) in form of a projected view on the horizontal plane, for the same time points (1) - (12) as it is marked in Fig.7. The intersection of the two axes is a reference point, moving with a constant speed equal to the mean speed of the model, and in a steady direction relative to waves, i.e. 30 degrees (mean heading angle). The submerged part of the deck is shadowed, and the black spots indicate the area where the dynamic pressure occurs. The position and direction of the wave crest is also marked. It can be seen that the dynamic pressure is not generated on the whole submerged surface.

The presented sequence of graphs illustrates very well the movement of the deck when the wave overtakes the model, and indicates the submerged area where the hydrodynamic effects are induced. This helps to understand better the cause of the strange roll behaviour in the analyzed run. The pictures are in a very good logical agreement with the roll motion in Fig.7 C.

Picture (1) shows the position of the deck at the moment of the wave impact on the stern. It is interesting to notice that at this time, large portion of the deck at stern was immersed despite the fact that at the midships the bulwark was not submerged.

Nominal forward speed V= 1.1m/s
Nominal heading angle μ = 30°

Periodic extreme waves with:
Nominal period T= 1.7sec.
Nominal height H= 0.6m

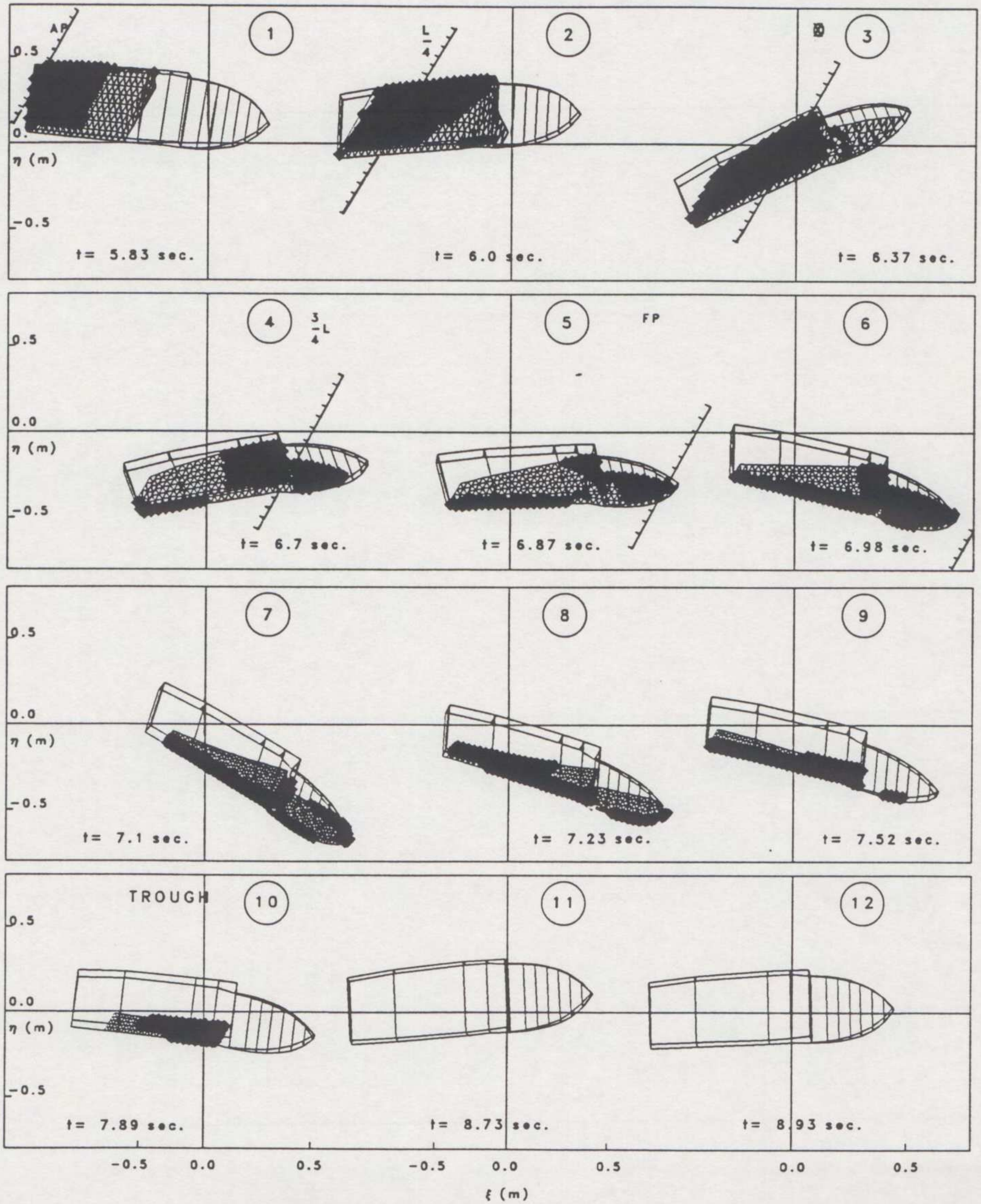

Fig.9 Deck submergence in a free-running model test in breaking quartering waves (Projection on the horizontal plane). Run No. 25. Time points correspond to those given in Fig. 7.

Hydrodynamic effects were induced on that part of the deck. This explains why the roll angle rapidly increased right after this time point, although the bulwark was not indicated as submerged in Fig.7 C.

The sequence of pictures indicate that when the wave crest was travelling between the stern and the midships, the hydrodynamic effects were generated on the after part of the deck. After the wave crest passed the midships, the bow part contributed mostly.

The most interesting information brought by this sequence of graphs is, that when the wave crest passed the bow and the model changed its yaw direction, so that the bow was moving back to weather side and thus, was running off the wave crest, the hydrodynamic forces were generated at the after part of the deck (p.(7)-(9)) while the wave crest was well ahead of the bow! This was caused by fast movement of the stern towards the lee side because of the yaw motion. Although relatively small portion of the deck was submerged, the pressure was induced close to the deck edge and the heeling moment was quite significant. This unexpected distribution of pressure explains to some extent the strange second peak in the roll motion (point (9)) when the model was on the back slope of the wave and thus, should vigorously roll back to the upright position.

Calculated dynamic heeling moment generated on the submerged deck, is presented in Fig.7D as a solid line. The dynamic moment reaches its maximum value when the wave crest is in the area of midships (point 3). It decreases rapidly when the wave crest advances towards the bow (point (4), (5)), and then increases again, reaching its second peak shortly after the wave took over the bow (point (6)). Then, it decreases slowly and varnishes shortly after the wave trough (between points (10) and (11)). The direction of the moment is from the weather to lee side, and thus, this is a heeling moment tending to heel the model further. Only the first two values (points (1) and (2)) have opposite sign, which is inconsistent with the model behaviour. This is caused by the fact that in the theoretical model, the wave diffraction effects, in particular the disturbances in the circular velocities at the lee side, are not considered. As a result, the dynamic pressure at the lee side is underestimated. This shortcoming has to be removed.

When comparing the dynamic moment with the history of roll in Fig.7 C it can be seen that the character of changes in both graphs match very well each other. When the dynamic moment grows reaching its peak, the roll angle increases as well and reaches the peak at the same time. When the moment decreases, the model starts to recover. The roll angle follows also the second increase of the dynamic moment. However, the second peak of roll is achieved later than the second peak of the moment, and is larger than the first one, despite the fact that the moment values are smaller at this time. This discrepancy was explained when the second effect of deck submergence, i.e. the additional static moment was calculated and introduced in the same graph 7 D (broken line).

The additional static moment reaches also two peaks for the same wave positions as the dynamic moment does. Surprisingly however, the second peak is in this case much larger than that for the wave at midships. As a result, the total heeling moment caused by bulwark and deck submergence (the sum of both moments) which is presented in Fig.7 E, has two distinct maxima: one, when the wave crest is in the midships zone, and the second one when the wave is in front of the bow. The second peak is larger.

Comparing now the total heeling moment with the history of roll it can be seen that the roll motion follows the changes of the moment generated on the submerged deck. When this heeling moment disappeared, the model started to recover from the large heel (shortly after point (9)).

In order to provide better explanation of the influence of the hydrodynamic effects generated by bulwark submergence, an example of the wave exciting moment is added to Fig.7 E. The dotted line represents a wave exciting moment exerted on the model in the partly-captive tests. This is not the real wave moment acting on the model in this run. The wave was different and the moment was measured in the model running in the upright position. However, it shows the direction of the moment due to wave action, and changes of its value when the wave is moving along the hull. Thus, only qualitative comparison can be made here between these two moments.

It can be seen that when the wave crest is moving along the hull, the wave exciting moment tends to heel the model to the opposite side. However, the moment generated by the submerged bulwark and deck counterbalances the wave moment. If the moment caused by deck submergence is larger than the wave exciting moment, the ship rolls further down, until the balance of the moments changes its sign.

The mathematical model of the effects on the submerged deck, used for the computations presented here, is still under development and requires further improvements. However, even in its present form, it provides a very useful tool for predicting the occurrence of this dangerous phenomenon and for estimation of its magnitude.

DECK EFFECTS IN STABILITY CALCULATIONS

Water on Deck or Deck in Water ?

The hydrodynamic effects on the deck immersed in water, should not be confused with the effects commonly called as "water on deck".

In the case of deep deck submergence, water situated above the deck constitutes a continuous extension of the surrounding water, and the velocity distribution in the flow depends on the velocity field in the adjacent water domain (Fig.10 A). The phenomena discussed in the previous chapters constitute the hydrodynamic reaction of the surrounding water to the movement of the submerged part of the deck and bulwark. The magnitude of the generated forces depends on the induced pressure on the submerged elements. This pressure is dependant on velocity distribution in the wave and on ship motions.

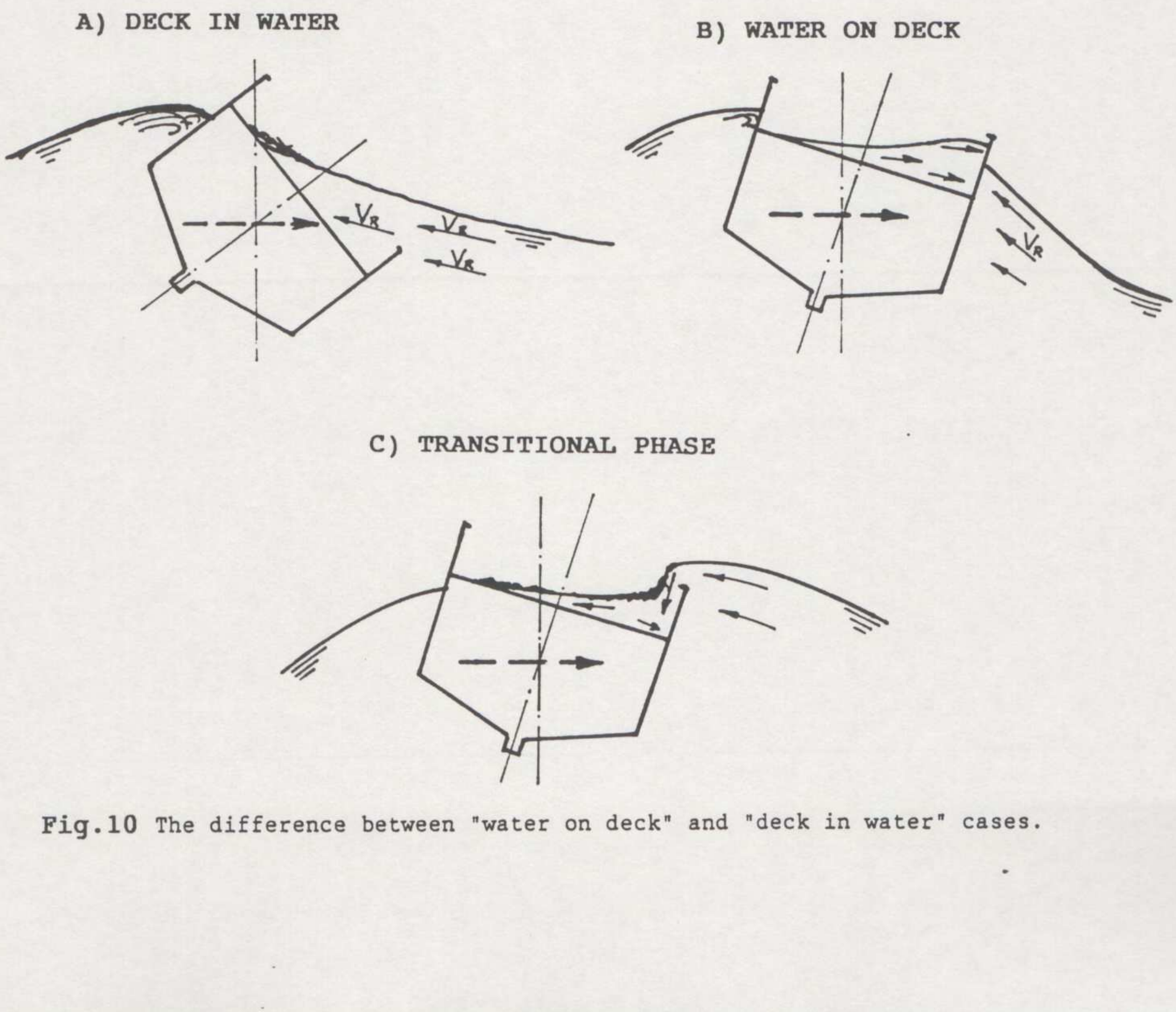

Fig.10 The difference between "water on deck" and "deck in water" cases.

In case of the classic "water on deck" situation, the mass of water trapped in the deck well is separated from the surrounding water. The movement of that mass and subsequently, pressure exerted on the deck depends on volume of the trapped water and on the motions of the ship (Fig.10 B).

These two cases are completely different and require different mathematical models.

During ship operation in extreme waves a combination of these two situations usually occurs, and some transitional phases comprise elements of both phenomena (Fig.10 C). The flow above the bulwark is governed by the difference between the water levels, and between velocity and pressure distributions inside and outside the deck space, and is strongly deformed. The mass of water trapped on deck is rapidly changing, while the hydrodynamic reaction due to bulwark submergence did not reach yet its full magnitude. The transitional phases are the most difficult for mathematical modelling.

Consideration of the Deck Effects in Stability Analysis and the Direction of Future Research.

In stability safety analyses used in practical applications, only the influence of water trapped on deck is recognized and taken into account. It is considered either as a reduction of the static stability due to, so called, free surface effect, or as a static load on the deck due to mass of water filling the volume between the bulwark and the deck, heeled to a particular angle (Torremolinos Convention for Safety of Fishing Vessels). The mass of water, and in result the heeling moment, depend on the deck well architecture and on the heel angle. This moment is used for evaluation of the balance of static stability of a ship operating in waves.

The hydrodynamic effects generated on the submerged deck were not recognized before, and they were not considered in any stability analyses. The results presented in this paper indicate how significant these effects are, and how large magnitude the additional heeling moment may reach in comparison with the moments traditionally considered in modelling of ship dynamics in waves.

It is worthwhile to point out that according to prediction methods commonly used at present, the wave exciting moment in the analyzed case would have a character similar to that presented by the dotted line in Fig.7E, and the roll response (calculated in frequency or in time domain) would be close to that presented by the broken line in Fig.7C. The difference in the behaviour of the ship is tremendous, and not only with regards to amplitudes of roll but first of all, in the character of roll. Without consideration of the deck effects the ship would be regarded safe, while the recorded real runs proved that the ship in these conditions is in danger of capsize (see Fig.8).

The effects created by bulwark and deck submergence have to be taken into account in any stability safety considerations. They should be included in the development of stability criteria, as well as in establishment of operational safety procedures. A mathematical model representing adequately the phenomenon discussed has to be developed in order to provide possibility of inclusion of these effects into stability analyses.

The mathematical model which has been developed so far, proves that these effects can be calculated and it provides a good base for further improvements. The main improvements should include:

1) Incorporation of a method for calculation of wave diffraction at the ship sides, including corrections of wave profile and velocity distribution. The method must provide possibility of calculating the deformation of wave profile and velocity distribution for a heeled position with the deck immersed, and not only for the upright position of the hull.

2) Theoretical model of water shipping on deck has to be modified in order to represent better the inflow in the early phase of bulwark immersion. Some hydraulic models may be adopted in combination with the relative velocities concept.

3) Mathematical model of dynamic effects of water trapped in the deck well has to be developed taking into account the changing mass of water caused by inflow of new mass from outside and escaping of some water from the deck space.

The mathematical model has to be validated and calibrated against experimental results. Special, dedicated experiments have to be designed so, that they could provide possibility of direct measurement of pressure and forces exerted on the deck and bulwark only. In addition, the inflow of water above the bulwark and the resultant mass of water shipping on deck should be monitored.

Once the mathematical model of the deck submergence effects is completed and validated, it should be used in stability analyses and predictions of ship behaviour in extreme waves. The logical and easiest way of using it would be to include this model into time-domain simulations of ship motions in extreme waves, and in the moments or energy balance methods.

CONCLUDING REMARKS

When the bulwark and part of the deck become submerged during ship operation in heavy seas, dangerous hydrodynamic phenomena are generated on the immersed part of the deck. They induce an additional heeling moment, not recognized before and not considered in any stability analyses.

The hydrodynamic effects on the submerged deck alter dramatically ship behaviour in waves, reduce significantly its restoring capability, and may cause a capsize of a ship, which according to the currently used stability standards is considered to be safe. The dangerous effects created by these phenomena have to be included in the stability safety analyses.

A mathematical model of the hydrodynamic forces and moments generated on the submerged bulwark and deck is needed, in order to provide the necessary tool for prediction and evaluation of the dangerous effects. Such a model should be used in evaluation of stability of a ship in heavy waves, and also in development of new stability safety criteria and operational guidelines for navigation in extreme wave conditions.

The results of the calculations presented in this paper indicate that the first version of the theoretical model developed, constitutes a good base for further development. The results are in a very good quantitative agreement with the measured behaviour of the model tested, and they explain very well the strange roll behaviour which was difficult to comprehend before. The model has to be improved and validated against experimental results. The experiments have to be specially designed so, that the effects on the submerged deck can be separated from the overall hydrodynamic forces, and directly measured.

Without the incorporation of the effects of deck submergence into the mathematical model of ship dynamics in waves, a theoretical model of ship stability will not be adequate, and will not provide sufficient safety level for a ship operating in waves.

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