Special Lecture

Topics on Ship Capsize

by

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1. Introduction

Although ship capsize has been a phenomenon of deep interest to naval architects and navigators since early times, its theoretical treatment is commenced only in recent years.

The background for performing such a theoretical consideration seems to be arranged gradually. Observation data of ocean waves as an external force are accumulated steadily and their spectral characteristics have been clarified fairly well. At the same time the estimation of ship motions as well as pressure distributions on ship hull has become possible by use of strip theory with accuracy of practical usefulness.

As a result we have reached the situation to proceed to clarifying the more complicated finite motion, capsize.

Since most of present equations of ship motion are derived under the assumption of linearity and infinitesimal motion, they are not expected fully effective for studying finite motion. Non linearity must be taken into account and interactions among forces which might be defined clearly in linear theory will necessitate a more penetrative insight into the mechanism of capsizing. Study of ship capsize remains, therefore, one of the most attractive, difficult as well as indispensable works assigned to navel architects.

In March 1975, there was held the International Conference on Stability of Ships and Ocean Vehicles at the University of Strathclyde, Glasgow, with about 150 participants. Twenty-four papers were presented which were classified and read at five session; 1. definition of stability, 2. environmental conditions and experimental studies, 3. theoretical studies, 4. correlations of theory and experiments and 5. application of research findings. It is interesing to find the session, definition of stability, where three papers discussed the problem from wide and fundamental point of view. Ninty percent of the participants expressed their hope of having the next Conference within two or three years.

In the autumn of the same year the fourteenth Internationl Towing Tank Conference was held in Ottawa, in which I. K. Boroday and N. N. Rakhmanin summarized a report on capsize, that is, "State of the Art of Studies on Capsizing", Report of Seakeeping Committee, Appendix 8.

Following problems are pointed out as future research targets in the conclusion of their report:

—investigation into hydrodynamic features of wave effect upon a ship floating at an arbitrary heeling angle including the values which exceed the angle of deck edge immersion;

—experimental and theoretical studies of the low-built ship motions, and of the dynamics of heeling and capsizing when green water is being shipped and trapped in the deck well;

—investigation into the dynamics of the process of heeling and capsizing under the action of a heeling load induced by the breaking waves;

—estimation of the effect of three-dimensional character of sea waves and the wave-induced rolling motions upon the restoring moment and dynamic stability of the ship in the following seas;

—investigation into the specifically hydrodynamic effect of the following seas upon the stability of ships moving at high Froude numbers;

—experimental and theoretical investigations of the conditons resulting in broaching and the peculiarities of the process of broaching;

—studies on the stability of rolling motion in a seaway at the external disturbances of finite value

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which are characterstic for various dangerous situations;

—estimation of the probability of capsizing in these dangerous situations when they are realized in a seaway;

—development of a rational system of criteria for the estimation of ship safety against capsizing in a seaway.

As the authors describe the above-mentioned does not cover all of the necessary points of importance and some of them have been partially solved by pioneer works, nevertheless, the validity of their indicating these items should be highly evaluated and the appearance of this report on the occasion was considered just opportune.

2. Two Big Disasters Experienced by Japanese Ships

Of the recent capsize casualties of Japanse ships the worst two were the loss of ferry boats including Toya-Maru and the simultaneous disaster of fishing vessels on Mariana sea area, where so many human lives were lost at the same time that intense social interest was concentrated to result in extensive investi gations into the causes of these disaters.

Fruitful investigation was carried out under the aid of favorable conditions that in the former occured the accidents in the vicinity of Hakodate Harbor with, in spite of over 1000 death, many survivors and in the latter, a number of ships operated in the neibouring area could survive and supplied valuable informations.

They are the very rare cases of capsizing in which the situation of the disaster in detail were comparatively well clarified.

Toya-Maru was a ferry boat of Japan National Railway, 113.20m in length and 4337 in gross tonnage. She left the pier of Hakodate-Harbor in the evening on September 26, 1954, with 1198 passengers and 133 crews as well as 12 coaches (weight 313t) and proceeded to the outside of the breakwater. Wind and waves due to Typhoon no. 15(Marie) were unexpectedly strong that she was forced to anchor there for standing sea forces, while the wind and waves grew up more and more and at about 19.30 sea water began to break into the wagon deck from the stern opening. She was drifted gradually to the sea-shore dragging anchors. At the time of 20.30 to 21.00 the highest wind speed of 57m/s was recorded on board, first the port side, next the starboard side main engine stopped at about 22.00, the bottom hull began to touch the sea bed at 22.30 and last capsize caught her at 22.45. 1084 passengers and 88 crew lost their lives.

At the same time Tokachi-Maru, Hidaka-Maru, Kitami-Maru and No.11 Seikan-Maru were capsized or wrecked in neighboring area with loss of human lives and cargos.

Extensive research works were carried out in collaboration of the University of Tokyo and ***Nippon Kaiji Kyokai*** in order to clarify the causes of this disaster, the technical result of which was published in [1].

The estimation descrided in the report is as follows: the wrecked vessels were standing the waves with the bow heading windward direction; due to extraordinarily high waves large quantity of sea water broke into the hull throngh stern opening and accumulated therein to reduce the metacentric height GM; some of the vessels were estmated to capsize due to negative GM; Toya-Maru was provided with passenger rooms outside of the wagon space which minimized the reduction of GM, however, at the moment of access to sea shore riding on the wave front, her bilge scratched unfortunately the sea bed to make her capsize.

It is also pointed out that, at the attack of Typhoon no. 15, sub low pressure came into appearance and lowered suddenly the advance speed of the Typhoon resulting in the misforecasting of the behavior of the Typhoon.

According to this bitter precept, Japan National Railway improved and strengthened the closing gear of the stern opening of ferry boats of their own.

Mariana disater (so called in Japan) arose in the neighborhood of Agrigan Island (145. 7°E and 18.8° N) in Mariana sea area on October 7, 1965.

Typhoon no. 29 born on October 4 moved northway slowly with zig-zag course and promptly developed to a strong gale with the minimum central pressure of 915mb and the maximum wind speed of over 70m/s. Of 10 fishing boats taking shelter around Agrigan Island, 6 were sunken and 1 was stranded with 209 losses of fishermen and crew.

The wrecked boats were tuna boats of 150 to 230 GT, being hitherto considered most reliable from the stability point of view. Investigation into the causes of the disaster was carried out basing the hearing of the testimony from crew of the survived boats as well as the survey of the damage left by the typhoon on many ships of neighbouring area [2].

The estimated causes are as follows:

1. Forecasting of development of the typhoon was difficult, which resulted in the capture of many fishing boats in typhoon centre.
2. Wind speed was extraordinarily high (70—80m/s). It was told that, at the time of the miximum wind, wave crests were suppressed and broken away by intensive and violently changing wind pressure, sea surface was covered with thick white spray and the vessels in the area experienced continuous large heel of over 50 degrees with little or no rolling.
3. Due to the large heel of long duration flooding came into existence through incomplete closing gears of various deck openings.
4. Because of too much severe wind and wave, it was impossible to keep the bow in opposing direction to wind even with full load operation of main engine. Reduction of main engine output might occur due to the remarkable decrease of atmospheric pressure as well as lack of fresh air supply caused by the closing of all openings.
5. Fishing vessels had larger wind area compared to other kinds of ship.
6. Freedom of ship operation was restricted by the island.

Common factor relating to both big disasters are that they were brought about by the formidable effect of typhoon and the difficulty of its forecasting. At present the techniques of weather forecasting and its tele-communication have developed so markedly that a part of the causes of such a disaster is supposed to have only little degree of danger. However the importance of weather forecasting *on board* to prevent desaster is not diminished since the state of wind and waves changes often abruptly with respect to time and/or space.

Probability of appearance of such a high speed of wind would be very low, nevertheless these disasters give us a valuable warning to terrible action of wind force, leading the author to the study of ship motions in strong wind.

3. Equation of Motion

It is a common way of engineering research to construct a physically reasonable model for actual phenomenon, which will be decribed most conveniently mathematical equations. As mentioned heretofore capsize is a complex motion with finite displacement and will be determined essentially by solving six component simultaneous differential equations. Until now, however, our knowledge on this phenomenon is yet so little that it will be meaningless to write down complicated system of equations formally. Therefore, a governing equation of rolling with one-degree of freedom is presented for convenience, taking formally the concept of infinitesimal motion into consideration.

As is well known, fluid force acting on ship hull moving in still water is divided into 1) the force due to displacement, 2) the ofrce due to relative velocity and 3) the ofrce due to acceleration. They are nominated as restoring, damping and inertia force respectively. In addition, external forces, such as wind and wave action, must be considered. They are now calculated under the assumption that they act on ship hull fixed in space.

Following this way of thinking the equation of motion will be expressed as follows,

$$(I+J)\ddot{\phi}+f_1(\dot{\phi})+f_2(\phi)=F(t), \qquad (3.1)$$

I=mass moment of inertia of ship about x axis,
J=added mass moment of inertia about x axis,
ϕ=angular displacement about x axis,
dot on ϕ=d/dt,
t=time.

x axis is the horizontal, fore and aft axis passing through ship's centre of gravity. Centre of added mass is assumed to coincide with that of ship's mass.

In equation (3.1) $-J\ddot{\phi}$, $-f_1$, $-f_2$ and F represents inertia, damping, restoring and external force respectively.

Even within the knowledge obtained until now f_1

can include $\dot{\phi}$, or f_2 relates to time explicitly or to other components of motion, so that attention must be payed not to consider equation (3.1) as mathematically strict expression.

Of the relating forces, inertia term $-J\ddot{\phi}$ is usually small enough compared to $I\ddot{\phi}$ and no more mention will be given in this paper.

4. Damping Moment

This term cannot be obtained by purely theoreical calculation even in the frame of infinitesimal motion theory because of governing effect of viscosity.

Part of roll damping is effected by eddy formation of bilge keels which have been used in practice for a long time. Damping force due to bilge keel is known to consist of fluid pressure acting on bilge keel itself and the pressure variation brought about on neighboring hull surface. Tanaka et al [3] measured and analysed the pressure distribution on rolling model ships and derived an experimental formula for practical use.

It is shown that the generated pressure variation follows $(\dot{\phi})^2$ and the back pressure on bilge plate depends on rolling amplitude. Dependence of f_1 on rolling amplitude has been well known, the main cause of which will be attributed to the characteristic of bilge keel.

Roll damping increases usually with advance speed [4, 5]. It is also noticed that the increase is not monotonous but undulating, suggesting the interaction between waves generated by rolling. No theoretical investigations have been made as regards this phenomenon.

Considering an excessive heel as approaching capsize, immersion of deck side and bulwark must be taken into consideration (especially in case of low freeboard vessels). In particular bulwark may be considered as a large sized bilge keel and possibly exhibit powerful damping. Very few reports have been published until now as regards the action of immersed bulwark. The author [6] performed an experimental research on the behavior of a model ship with the initial condition of immersed bulwark and found occurrences of large angle of continuous heel sometimes, the analysis of which could not be carried out further.

From the ship safety point of view it will be recommended that ships are designed and operated not to experience such a large angle of heel as bulwork immersion take place. However, the study of such an extreme condition is inevitable to be able to take adequate measures to meet the dangerous situation actually in existence.

5. Restoring Moment

There seems to be nothing to discuss as regards restoring moment in still water, however, a minor problem, the effect of trim on statical stability, will be described in the following.

Restoring moment $f_2(\phi)$ is given usually in a form of "curve of statical stability lever GZ", which is calculated under the condition of constant volume of displacement allowing only vertical displacement of fore and aft axis of ship with zero trim. On the other hand, if an external moment around the fore and aft axis is given to a ship floating freely, she will, in general, have a heel as well as a trim, resulting in a reduction of statical stability for prescribed value of heel angle. An example of the measurement [7] of GZ of a model is shown in Fig. 1. Approximate calculation taking the trim angle into consideration is also shown in the figure. The reduction in GZ is only considerable at large angle of heel, so that it gives only minor effect to ship motion in usual form of ships.

Although f_2 can be expressed as a linear function

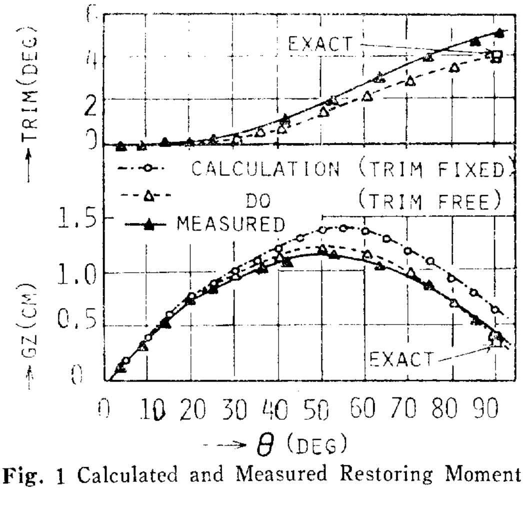

Fig. 1 Calculated and Measured Restoring Moments

for sufficiently small ϕ, nonlinearity of f_2 must be considered for the motion with finite displacement. The behavior of oscillating system with nonlinear restoring force (or moment) has been studied rather well and several methods of approximate calculation are published for practical use. It is self evident considering a simplest case of constant heel moment, that the linearity in GZ provides arbitrarily large stability, however, a vessel can at most stand F_{max} statically and F_{cr} dynamically according to the manner of loading. F_{cr} is determined from the condition that the area OAD equals to the area ABC(Fig. 2).

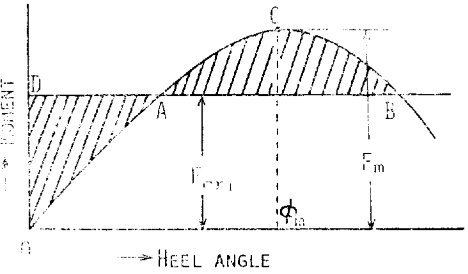

Fig. 2 External Moment Applied Statically or Instantaneously

The effect of non linearity in f_2 will be considered later again.

We shall proceed to consider the change of f_2 in waves. Owing to the change of pressure distribution in longitudinal wave there arises the variation of f_2, a decrease in wave crest and an increase in wave trough. The variation is largest in waves of the length indentical to ship's length. Since the advance speed of ship is, in general, different from that of waves, the ship will run in waves with a period of encounter T_e and f_2 is expressed approximately as follows,

$$f_2 = a(1+b\cos\omega_e t)\phi, \qquad (5.1)$$

where a and b are constants and $\omega_e = 2\pi/T_e$. Due to the term cos $\omega_e t$ there comes into existence a possibility of apperance of Mathieu type unstable rolling, which was also confirmed by several experiments. Though the unstableness is not always combined with capsize because of dependence of F_1 on ϕ etc., it is conceivable that the Mathieu type unstableness takes an important role on capsize in following waves, where ω_e can be small enough giving sufficiently long interval of dangerous situation.

Y. Watanabe [9] pointed out that the trim ψ is followed by the vertical displacement of centre of buoyancy by $\frac{1}{2}$ $BM_1\psi^2$, resulting in considerable loss of GM because of large BM_1. By the fluctuation of ψ in waves there can appear also Mathieu type unstableness. This is an example of interaction between rolling and another motion component.

Ship have steady heel under the action of strong wind pressure in rough sea. If there is, in addition, a large heave superposed and immersion of deck edge realized, a new component of heeling moment comes into existence [10, 11] (Fig. 3).

When a ship dips down with heel angle ϕ_0, a heeling moment is composed between the buoyancey ΔV and the corresponding inertia force. (With zero heel angle, this moment is also zero.) An example of calculation for a cylindrical ship is shown in Fig.4,

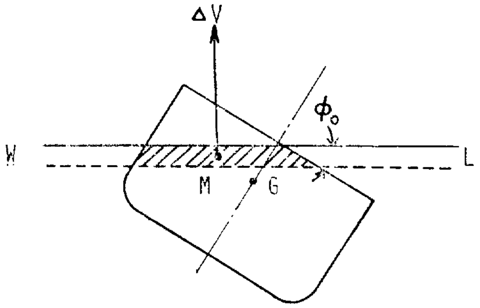

Fig 3. Excess Buoyancy Due To Heaving

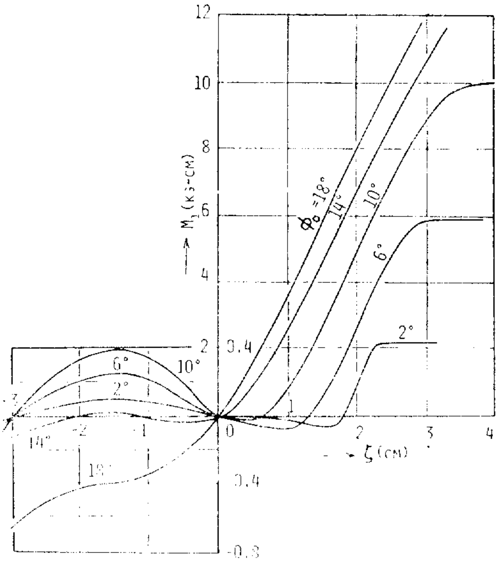

Fig 4. Heeling Moment Due To Excess Buoyancy

where strong nonlinearity as regards heaving amplitude and a peculiar tendency with respect to ϕ_0 are observed. Considering such an effect of heaving the author could give an explanation of the result of capsize experiment of box-shaped vessels to a considerable extent [10, 11, 12, 13]. The effect of the above mentioned heeling moment is supposed to be more conspicuous in low freeboardships, which may offer one of the theoretical bases for the safety regulation adopting ample transverse stability and freeboard as the most important factors.

6. External Forces

Wind and waves are the main external forces to be considered. In addition, icing exerts strong influence upon ship stability, however, mention will be omitted here as it is able to be cansidered as the variation of statical stability and augmentation of wind area.

6.1 Wind Force

The simplest model for ocean wind is an uniform air current having a representative velocity of actual wind.

However it is usual to make to a little more elaborate flow model of large scaled turbulent boundary layer in which wind speed increases with vertical distance from the sea surface. This means that wind pressure is relatively much more intensive at higher parts of ships and its exact estimation is inevitable. Power or logarithmic law of velocity distribution is available for this purpose.

Actual ocean wind is, however, a stochastic random process like as ocean waves, the mechanical characteristic of which is expected to be described completely by energy spectrum. Unfortunely reliable data of wind spectrum are not abundant up to the present, mainly due to the difficulty of accurate measurement of wind speed over sea surface. Different conditions from the observation on land are: difficulty in getting fixed base for measurement: existence of disturbing effect of ship forms and motions: disturbance due to waves and sprays near the sea surface and limitation of observation height etc.

Difficulties for theoretical approach have to be overcome as well with regards the fact that the boundary consists of freely deformable water surface and energy can be exchanged through this surface resulting in strong interaction between air and water flows of boundary layer.

These circumstances seem to be a reason why no treatments for the estimation of ocean wind force have been performed until now taking energy spectrum into consideration.

Air current in laboratory is generated intentionally, at least, as steady flow with respect to time, however, coexistence of artificial waves calls forth a disturbance against the steadiness of the current. Wind speed increases over wave crest and decreases over wave trough, which results in giving a periodical fluctuation of wind pressure upon ship structure. In a stormy wind this effect might not be overlooked, the effect being supposed severe to small vessels.

Under the action of wind force ship drifts leeward, which generates underwater drifting force to counteract the wind force. T. Hishida [14] found that the centre of effort of water pressure is displaced vertically upwards with drifting speed when it is assumed that the heeling moment is composed of horizontal components of wind and water forces. The vertical displacement varies also with the heel angle in complex manner as making capsize by wind force only somewhat difficult to occur.

Theoretical studies of drifting forces in waves have been carried out actively in recent years, however, in case of steady flow the effect of viscous drag dominates, of which estimation is yet difficult.

In experimental study of wind forces, it becomes frequently a problem of argument how to realize a condition of water surface. Two methods are practised, that is, a) the measurement in large wind tunnel simulating water surface by suitable means, and b) the use of wind blowing facilities over model basin.

The author made several experiments using the latter method, from the experience of which he believed that the wind blowing facilities constructed hitherto are not sufficient. Considered as a whole together with model basin, the uniformity of current in space and time is not secured in full extent, leading to the difficulty in mutual comparison of the data obtained at different organizations.

6.2. Wave Forces

Wave forces on ship are divided into two, the first due to fluid pressure on outer shell and the second due to fluid pressure on deck and inside of bulwarks though on occasion of immersion of bulwark top at large heel the division becomes non sense.

It has been clarified [15] that fluid pressure on outside shell can be estimated considerably well by so-called strip theory except impulsive pressures. Impulsive pressure may sometimes be of great importance to structural members but it is supposed to affects rarely to ship motions. The intense impact of water mass of considerable scale might only be a cause of capsize if it occurs unfortunately at the worst instant of ship motion. There are several wave systems travelling in different directions in the ocean and the existence of pyramidal wave is also well known by seamen, so that the possibility of collision of such a steep, high wave with ship hull can not be denied completely.

The method of experiment using concentrated transient waves developed by S. Takezawa [16] for studying wave impact load is noteworthy enough for the research of capsizing of this kind.

Wave forces of the second type are produced usually by shipping of green water. It is not difficult to calculate the influence of shipping water statically ignoring freeing ports, however, only a few has been published as to its dynamical action.

A compact expression for this is given in a report [17] emphasizing an effectiveness of the action over much wider range of heel angle. Because of the complicated arrangement of hatches, deck houses, winch tables and so on, the estimation will be rather difficult for practical use.

Most of the past investigations into shipping water are related to the probability of occurence, while I. Takanashi [18] carried out the experimental research on the quantity of shipping water. He derived an empirical formula successfully and proceeded to calculate heeling moment as a function of time. Assumption were made of zero advance speed and the regular oncoming beam seas.

According to Takanashi the quantity Q of shipping water in one cycle is given by the formula,

$$Q=0.65V_0H_0T_0 \tag{6.1}$$

where

$$T_0=\left(\frac{1}{\pi}\right)T_w\cdot\cos^{-1} k,\ k=f/Hb, \tag{6.2}$$

T_w=period of wave,

f=effective freeboard,

Hb=wave height at ship's side of sufficiently high, imaginary freeboard,

$$H_0=0.83\psi\ \sqrt{1+15\mu^2}/\sqrt{1+60\mu^2}, \tag{6.3}$$

$$\Psi=Hb-f, \qquad \mu=\sqrt{\psi/gT_0^2},$$

$$V_0=0.65\sqrt{g\Psi}/\sqrt{1+15\mu^2}. \tag{6.4}$$

Hb is defined as mentioned above, however, if it is obtained by calculation, the restriction of “sufficiently high” is not necessary because the calculation theory of present time assumes infinitesimal amplitude of waves.

Formula (6.1) shows that a stream of maximum height H_0 flows in over bulwark top with average velocity V_0 during the time interval T_0 when Hb is greater than f.

Heeling moment due to shipping water is calculated under the assumption that it consists of the impact of falling water, the weight of staying deck water and the impact on leeside bulwark. Fairly good agreement with experiments is obtained, but the effect of shipping water on ship motions, especially on capsize, is not yet discussed in his work.

As regards spectral structure of ocean waves which is the real source of wave forces, the situation has reached the step where the discussion of two dimensional (directional) spectrum is central topics with increasing accumulation of reliable wave data. In order to take account of the directional distribution of wave enargy, the coefficient in the form of $\cos^n\theta$ ($|\theta|\leqq\pi/2$) is used widely.

According to H. Mitsuyasu [19] the dispersion represented by the index n depends also on the frequency of component waves. It takes large value in the vicinity of the frequency of maximum energy density indicating weak dispersion, while smaller values on n are observed at both of lower and higher frequency regions.

6.3. Example of Ship Motions under Coexistence of Wind and Waves.

An example of experimental results will be described of the motions of ship model under the simultaneous action of wind and waves. If a model ship is subjected to such an effort, she will make rollings around a constant heel under the assumption of linearity. Change of wave period keeping constant speed of wind makes the roll amplitude increase or decrease with constant heel. Increasing wind speed under constant waves will bring about larger heel only. In Fig.5 the result of experiment is shown for the case of varying wave period under constant wind speed, while Fig.6 indicates the result obtained in constant waves and varying wind speed [6]. It is observable in Fig.5 that θ_0, the mean angle of heel, changes with wave period even in constant wind.

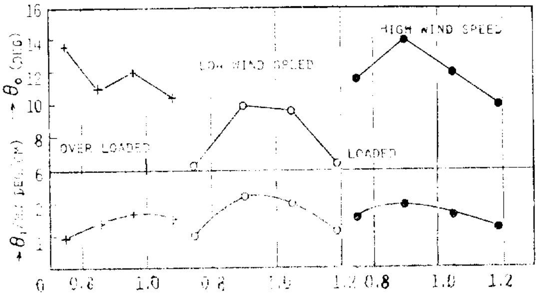

Fig. 5. Heel Angle and Amplitude of Rolling under Various Wave Periods and Constant Wind Speed.

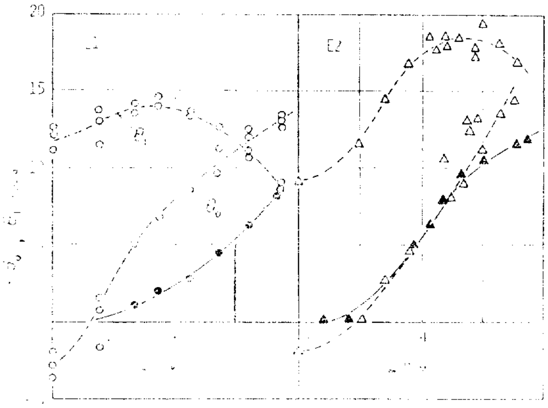

Fig. 6. Heel Angle and Amplitude of Rolling under Varying Wind Force
(E1:Full load, E2:Half load, ▲●:without waves)

Though increase of θ_0 with increasing wind speed is natural, the amplitude of rolling, θ_1, also reveals considerable variation with a peak point in Fig. 6. One of the main reasons for appearance of these results is believed to be nonlinearity in the curve of statical stability.

An illustrative calculation of nonlinear oscillation is developed in the following.

Let us consider an equation of rolling in waves with non-linear restoring moment,

$$I\ddot{\phi}+N\dot{\phi}a+W_1GZ\ (\phi_a)=M, \tag{6.5}$$

where

ϕ=absolute angle of rolling

$\phi_a=\phi-\phi_w$=relative angle of rolling to wave slope

I=total mass moment of inertia

N=coefficient of roll damping

W=displacement of ship

M=heeling moment (except that of waves).

Approximation is made of the wave excitation moment in the statical expression $W\cdot GZ\ (\phi_a)$.

For simplicity the case of constant I, N and M is considered. Further we assume that

$$\phi_w=\phi\sin\omega t \tag{6.6}$$

and

$$GZ=(GM/p)\ \sin\ (p\phi_a) \tag{6.7}$$

equation (6.7) prescribing a constant initial stability (=GM).

Approximate solution for ship motion with circular frequency ω is assumed as follows,

$$x=p\phi_a=X_0+X\sin\ (\omega t-\varepsilon), \tag{6.8}$$

where X_0, X and ε are unknown constants to be determined.

Expanding GZ in Fourier series with respect to time and comparing the coefficients of both sides of equation (6.5), we can obtain the following three simultaneous equations to determine X_0, X and ε.

$$\left.\begin{array}{r} -X+2bJ_1(X)\cos X_0=-c\ \cos\varepsilon \\ aX=-c\ \sin\varepsilon \\ J_0(X)\sin X_0=-f_0 \end{array}\right\} \tag{6.9}$$

where

$a=N/I\omega$,

$b=W\cdot GM/I\omega^2$,

$c=P^{\phi}$,

$f_0=M/WGM$

J_0, J_1=0th and 1st ordedr Bessel functions of the 1st kind.

Equation (6.9) can be solved numerically or diagramatically and the calculation result for $c=0.8$ is shown in Fig. 7, from which we can observe a discontinuous jump in X_0 and X with increasing f_0. The abscissa is the ratio of natural rolling period to wave period. It is also noticed that X_0 varies with wave

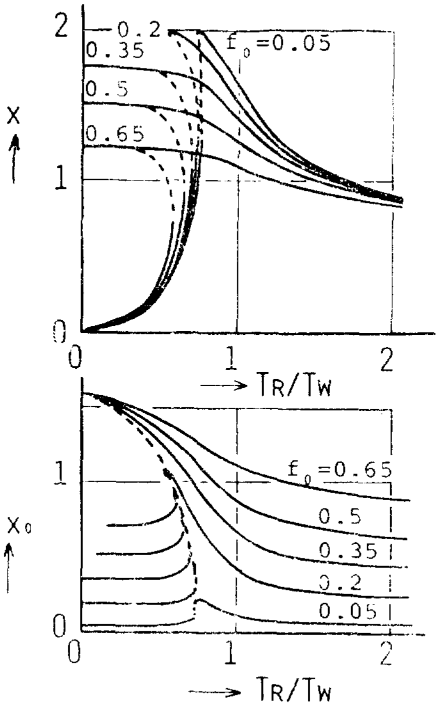

Fig. 7. Mean Heel (X_0) and Amplitude of Rolling (X) under Constant Heel Moment (f_0) and Wave Action.

period under constant f_0. Part of X_0 and X in dotted curves in the figure are unstable and not realizable, and it was found by analogue simulation that capsize may occur in the transient from a stable value to another [20].

7. Capsize at the Moment of Crossing Flow Region

Kurushima Strait is located in Seto Inland Sea of Japan and well known as a dangerous spot of very strong current.

Capsize accidents at midnight occurred in succession in the springs of 1972, 1973 and 1974 at the moment of highest tide.

Vessels are estimated to capsize at the time of crossing out the current boundary by steering port side on southward current(Fig. 8).

A cement carrier of 2600GT and 79m in length was capsized in 1974, the stability of which satisfied the requirements of Stability Regulation of Japanese Government except that of maximum GZ, the actual value being only 0.14m against the requiremant of 0.275m.

Simplified distribution of current velocity on the line AB is drawn separately in Fig. 8. There is a region II between region I (current) and region III (weak reverse flow), where flow velocity changes with large gradient. The region is nominated here as shear flow region. If the width of the region is small compared to ship's length, the ship will be subjected to different kind of fluid pressure of fore and aft parts of the hull.

Simplified model of the situation is illustrated in Fig. 9 where fore half of the ship in a leftward current and aft half is in still water. Transverse fluid force due to current is counterballanced by inertia force, of which the component due to virtual mass makes approximately no heeling moment since its centre of effort is located in the vicinty of that of current force. As a result the net heel moment depends on the magnitude of inertia force due to ***ship's mass*** acting at centre of gravity. Under the influence of the external force shown in Fig. 9 the ship begins to turn to the left resulting in the increased contribution of centrifugal force to heeling moment. As centrifugal force is proportional to advance speed as well as yawing rate, large heeling is apt to occur with large values of the two factors, leading to possible danger of capsizing.

Experimental investigtions were carried out at a model basin of the University of Tokyo in order to study fluid forces exerted on ship hull in shear flow [21].

Model shear flow was realized at the boundary of the wake generated by a row of vertical square pillars fixed to the running carriage(Fig. 10).

Fluid forces were measured at various locations of ship's centre of gravity in shear flow region, the heading angle being varied in wide range.

An example of the measurement is shown in Fig. 11. Analysing these reults it was found that the fluid forces in shear flow can be expressed approximately as follows,

$$Y' \equiv Y/\frac{\rho}{2}LdU_0^2 = \frac{1}{2}(aA_1 + bA_2) \qquad (7.1)$$

$$T' \equiv T/\frac{\rho}{2}L^2dU_0^2 = \frac{1}{4}(aA_2 + bA_3) \qquad (7.2)$$

where

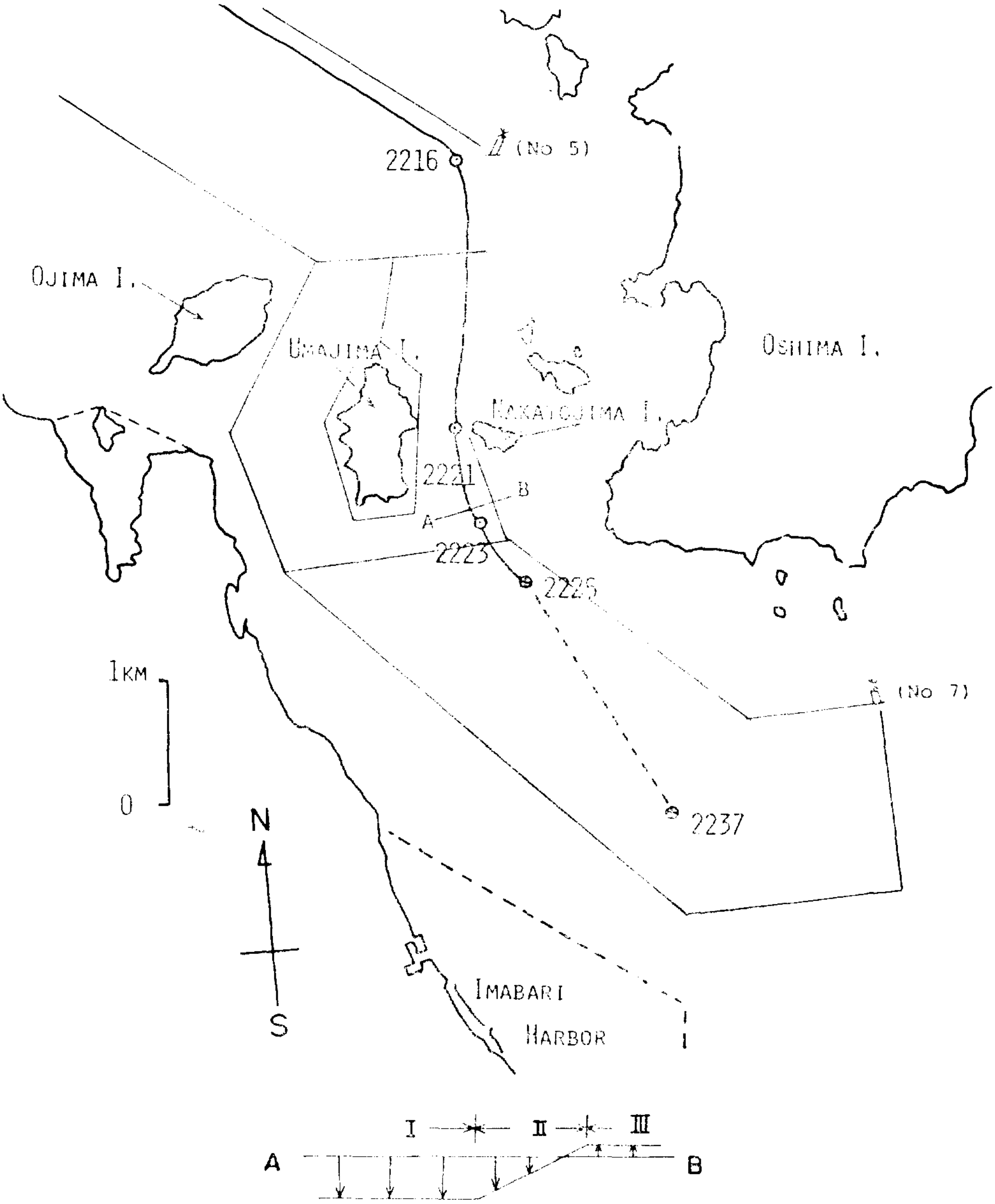

Fig. 8. Estimated course of the wrecked vessel

Y=transverse force,

T=yawing moment about vertical axis through centre of gravity of ship,

L=ship length,

d=ship draft.

U_0=relative speed of water at centre of gravity of ship,

u=relative speed of water at ξ on centre line,

ρ=density of water,

$$A_i=\int_{-1}^{1}\left(\frac{u}{U_0}\right)^2 \xi^{i-1}d\xi. \tag{7.3}$$

ξ is non dimensionalized distance of the squate station

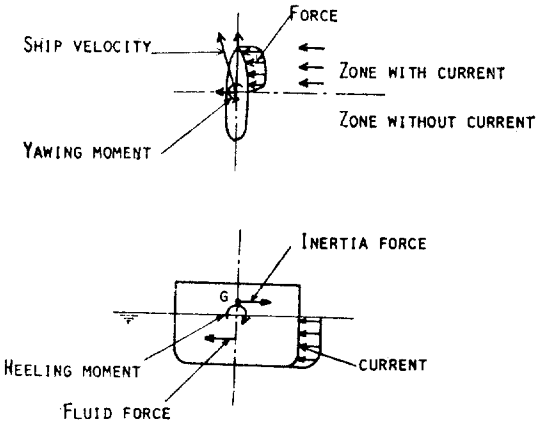

Fig. 9 Simplified Model of a Ship in Shear Flow

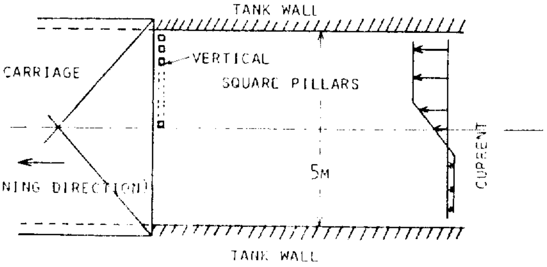

Fig. 10 Arrangement of Shear Flow Experiment

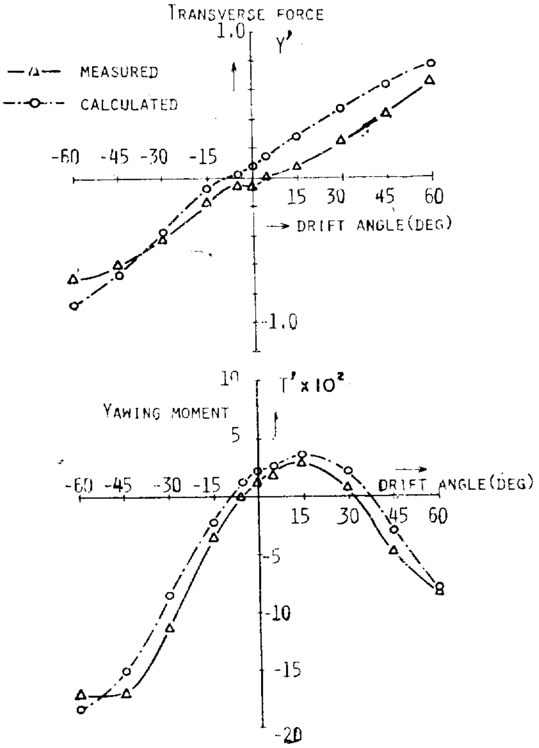

Fig. 11 Transverse Force and Yawing Moment, Measured and Calculated

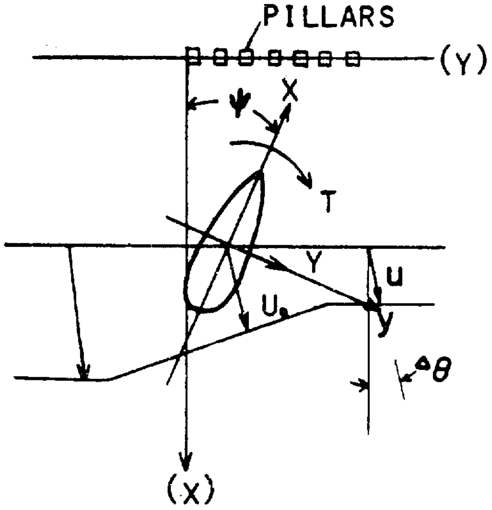

Fig. 12. Notations

forward of midship section, the unit being taken as $L/2$.

Two coefficients a and b are determined from the measurement in still water (where $u \equiv U_0$), that is

$$\left.\begin{aligned} a(\theta) &= Y_0' \\ b(\theta) &= 6T_0' \end{aligned}\right\} \qquad (7.4)$$

where subscript 0 signifies still or uniform water and θ the drift angle (Fig. 12).

The expressions (7.1) and (7.2) are derived under the assumption that the fluid force acting on the elementary area between x and $x+dx$ is written as $(\rho/2)u^2Cd\cdot dx$ with a linear weight function $C=a+b\xi$.

Calculations of ship motions were performed taking the expressions (7.1) and (7.2) into consideration for fluid forces in shear flow, the result of which clearly indicated the importance of;

1) lowering of advance speed,

2) taking full care to keep away from the situation receiving shear flow normal to the centre plane,

3) keeping straight course as much as possible and

4) securing ample GZmax

for preventing casualty.

Ship motions in waves as well as performance of screw propeller in non uniform wake are investigated extensively, however, transient ship behavior such as observed in shear flow region seems not to be studied hitherto, and further basic researches are considered necessary.

This sort of capsizing resembles to that due to broaching in the meaning that they are a kind of transient motion rather than periodical one and centrifugal force plays an important role.

8. Effect of Higher Order Term

S. Motora derived a system of equations of ship motion in well-ordered form of symmetry basing the technique used by H. Lamb [22]. For rolling motion, the equation is expressed as follows,

$$(I_x+J_x)\ \frac{dp}{dt}=(m_y-m_z)wv+(I_y-I_z+J_y-J_z)$$
$$qr+L. \tag{8.1}$$

Right hand coordinate system (x,y,z) fixed to ship is used, in which x is the fore and aft axis, z the vertical axis and the origin is located at the centre of gravity, u,v,w is the component of linear velocity and p,q,r is that of angular velocity respectively. Virtual mass m_y, etc. and virtual mass moment of inertia J_y etc. are also included with external moment L.

The first and second terms of right hand side of (8.1) are neglected in usual since m_y, I_y and J_y nearly equals to m_z, I_z and J_z respectively and, in addition, wv and qr are considered infinitesimals of higher order.

However there may yet be room for investigating the correctness of the treatment.

First, though m_y and m_z are quantities of same order of magnitude, they are so large compared to m_z that the difference between them could not always be ignored. In fact there is found by strip theory the existence of frequency regions where m_z is clearly larger than m_y. The same precaution may be necessary as to difference J_y-J_z.

Second, the assumption of small u and p etc. is allowable for the motion in waves, but v or r can be a term of O(1) in case of drifting by strong wind or turning motion.

putting together the above-mentioned, the neglection of the terms refered tonight lead to erroneous conclusion in some cases.

Since no further investigations have been made, the author remains only to call attention to this problem.

9. Final Remarks

Taking care of stochastic character of ocean waves some considerations were already made in the establishment of stability Regulations of Japanese Government in 1950s.

Many study works on safety of ships in random waves have been carried vigorouly in recent years from the standpoint of probabilistic considerations, some of which have made endeavor to include nonlinearity [23, 24]. The conclusions of these research works may possibly affect the design procedure or design itself of merchant ships.

In author's opinion, however, there remain as yet many problems to be solved fundamentally, for exxamle, the spectral structure of ocean wind and so on, and theoretical as well as experimental investigations into capsize are still a matter of urgent necessity.

More-over ships of new type as hydrofoil craft or hovercraft have come into existence, huge ocean strutures of different styles are also constructed in succession.

Further treatment for safety of these vehicles and structures is needed with possibly some new findings of the features of capsizing phenomenon.

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