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11. An Analysis of the Manoeuvrability of a Ship Associated with Unusual Characteristics Under Steerage

Seizo MOTORA*, *Member* Matao TAKAGI**, *Member* Akihisa KOKUMAI**, *Member*
Hiroharu KATO*, *Member* and Takeo KOYAMA*, *Member*

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Summary

In this paper, the authors deal with the manoeuvrability of a ship which was reported to have shown an excessive yawing and rudder motion under automatic control. Result of spiral test has also shown that the ship responds quite capriciously at small rudder angle; i.e. the ship sometimes switched direction of turn without any change of rudder angle, and most of cases, periodical yawing of about 90 seconds was superposed. The authors, having assumed these phenomena to be induced by unsteady hydrodynamic forces caused by separation of the boundary layer, conducted experimental investigations using a free running model as well as a restrained model. Flowline observations have also been conducted on an image model in a wind tunnel. Analysing results obtained, the authors proposed a hydrodynamic explanation of this unusual behavior of the ship that it must be caused by a combination of periodic change of hydrodynamic yawing moment and an abrupt change of yawing moment on the drift angle basis.

1. Introduction

Recently, in keeping with rapid enlargement of tanker size, phenomena supposed to be due to separation of boundary layer have appeared. So called instability phenomena regarding resistance and propelling performance[1] and those designated as so called abnormal phenomena in manoeuvrability[2),3] are those phenomena. Especially, the abnormal phenomena in manoeuvrability appeared only in model ships till quite recently, and did not occur in ships, accordingly correlation of model and ship was made extremely difficult.

In case of large tankers, the abnormal phenomena in manoeuvrability appeared mainly in such form that course stability was improved remarkably within range of not very large angular velocity of turning, and hydrodynamical explanation has been attempted but they are not yet explained perfectly.

On the other hand, not only in large ships, but also in fishing boats and other small ships, the abnormality in manoeuvrability supposed to be due to separation of boundary layer has been found in somewhat different form. As one of them, it has been reported[4] that a fishing boat sometimes responded capriciously and indefinitely to small rudder angle, that yawing occurred though the rudder angle was kept constant, and that the random response to small rudder angle was improved remarkably by attaching horizontal fin a little in front of stern bossing.

Being informed by trial result that the similar phenomena took place in a cement carrier recently, the authors attemped to examine hydrodynamically the mechanism

* Engineering Faculty of Tokyo University
** Research Institute, Hitachi Shipbuilding and Engineering Co., Ltd.

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to cause the abnormal phenomena through model experiment and counter measures to it. As the result, explanation qualitatively reasonable in way seemed to be attained. Therefore it is just reported herein, and comments of investigators concerned are invited.

Of course, the problems of this sort are quite complicated and cover many fields, and it is impossible to elucidate it fully in a short time. The authors hope that the present paper leads to more exact elucidation by suggesting the problems in the form of one attempt to explain the phenomena.

2. Phenomena in ships

2.1 Manoeuvrability at the time of auto-pilot in action

Firstly, the phenomena taking place in a ship are described, which motivate directly to lodge the problems. Principal particulars of the ship are shown in Table 2.1, and her body plan is given in Fig. 2.1.

From common knowledge in the past, it has been difficult to suppose that course keeping properties with auto-pilot pose operational problems for such type and rudder area as this ship, but periodical yawing of large amplitude occurred during straight advance with the auto-pilot in fully loaded condition, and it was impossible to reduce

Table 2.1 principal dimensions

L	100.0 m
B	16.4 m
d	7.0 m
Cb	0.746
V	12 kt
A_R/Ld	1/56

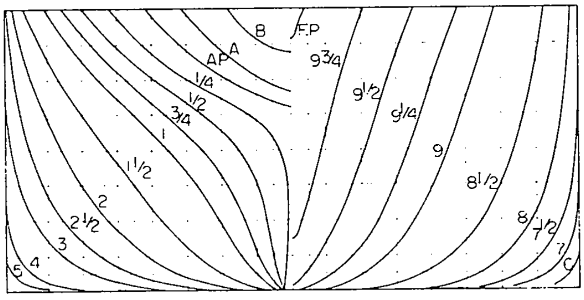

Fig. 2.1 Body plan

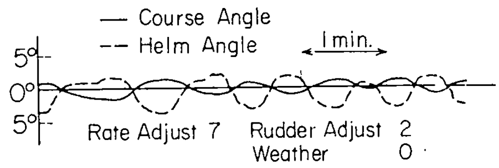

Fig. 2.2 Record of course and rudder angles when auto-pilot was used

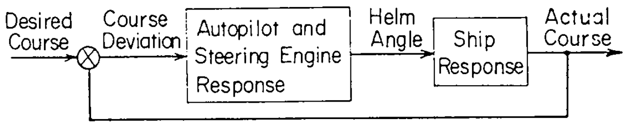

Fig. 2.3 Block diagrams of auto-pilot system

the amplitude below about 3° even by changing each adjustment of the auto-pilot. In addition, the period was about 90 seconds regardless of the rudder angle. Fig. 2.2 shows a part of records for heading and rudder angle of the ship.

In order to investigate characteristics of automatic control system with the auto-pilot of this ship as shown in a block diagram of Fig. 2.3, by changing periodically its course setting knob for automatic steering to right and left during sailing, the rudder and the heading angle at the time were measured, and frequency response of the closed loop was determined, input of which is difference between setting course and actual one and output is the actual course. An example of the measurement is shown in Fig. 2.4, and standard input was given by operating the course setting knob periodically like trapezoidal waves as shown by a broken line in the figure, instead of sinusoidal one. Analysis was carried out according to equivalent linearization method. As amplitude of the trapezoidal wave-like set course 3° and 5° (one side) were taken, but difference in results of the analysis was hardly observed between the cases. Thus, without discriminating the both cases, gain and phase difference are plotted with respect frequency in Fig. 2.5. It may be considered that to change the set course periodically is equivalent to that periodical external force acts on the ships, and phase margin in this case

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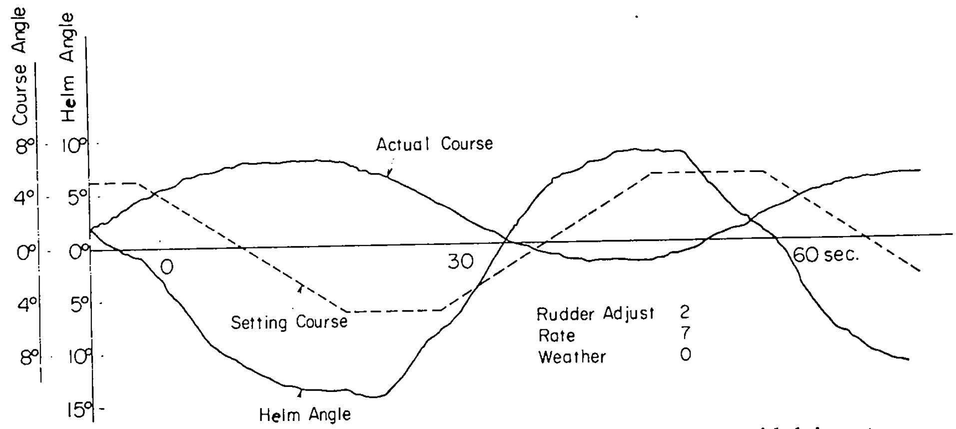

Fig. 2.4 Records of frequency response test by trapezoidal input

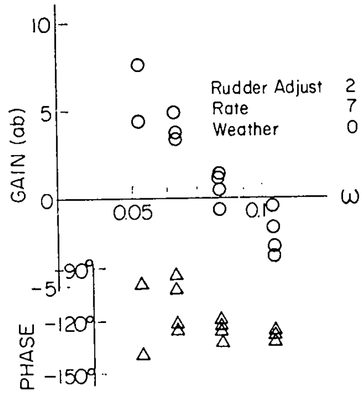

Fig. 2.5 Frequency response of loop transfer function

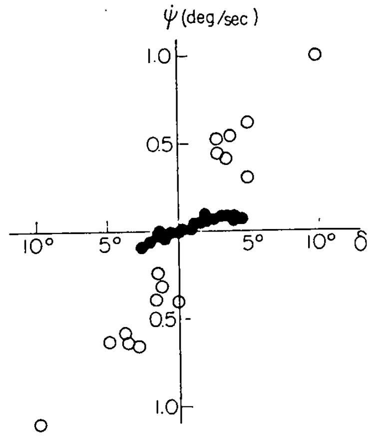

Fig. 2.6 Result of spiral test

was about 50° as seen from Fig. 2.5, showing that the automatic control system was stable.

2.2 Spiral test

Results of spiral test for the ship are shown in Fig. 2.6. In this test, steady turning angular velocity was measured, while the rudder angle was kept constant. As shown in Fig. 2.7, in case of small rudder angle, the angular velocity did not settle at constant

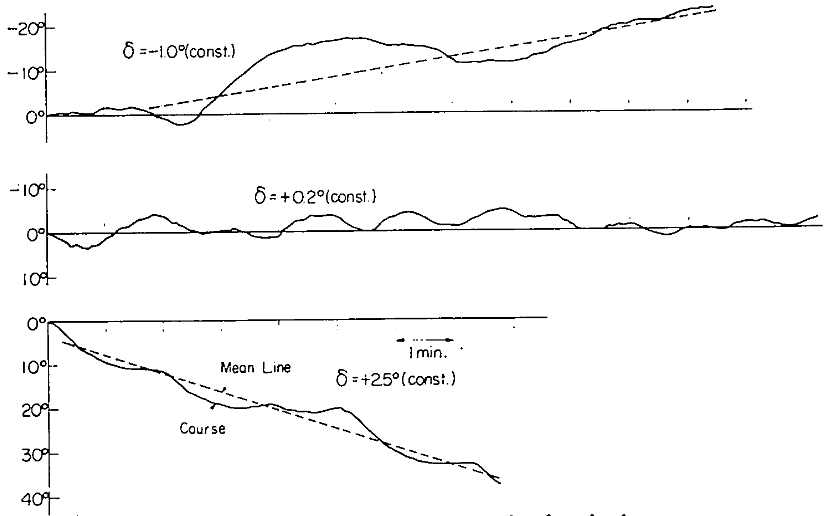

Fig. 2.7 Typical course record of spiral tests

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value, but phenomenon of periodical fluctuation (period; nearly 90 seconds) occurred, and sometimes direction of the turning suddenly varied. Black circles in Fig. 2.6 are average angular velocity read from the broken line in Fig. 2.7 for the case of appearance of such phenomenon. This figure represents that average course stability is good at small rudder angle, but it is unstable in a sense that turning angular velocity fluctuates. (White circles in Fig. 2.6 show the case that the angular velocity of turning did not vary, but settled at constant value.) These phenomena seem to be similar to those that frequently appear in model ships of full shape.[2),3)]

3. Phenomena in model ship

3.1 Spiral test of naked hull

As means to investigate the abnormal phenomena in ships and to look for countermeasures to improve it, model test is useful if it is reliable. Therefore first, spiral test was carried out to examine whether the abnormal phenomena occurred in the ships are reproducible with model ships.

The model ship used is a wooden model of L_{pp}=263 cm, equipped with radio steering appliance capable to steer by 1° per pulse, and can run at V_m=92 cm/sec using storage battery on board as power source. Employed water area was the seakeeping basin of the University of Tokyo, and condition was quite excellent because calm condition was guaranteed by covering roof. However, measurement was limited to only one plot by one test because the water area is narrow. A method was adopted in which initial angular velocity was given by taking larger rudder angle than the one set for the test initially, and afterwards the prescribed rudder angle was recovered. The angular velocity and rudder angle were recorded on recorders in the model ship.

The result thus obtained as shown in Fig. 3.1. Connection with arrow marks in this figure means that the angular velocity varied within the range in spite of constant rudder angle. Though the variation appears random at a glance, at times distinctively periodical fluctuation as seen in case of the ship might occur, and it seemed to occur frequently at small rudder angle of 1°–3°. An example of the periodical fluctuation is shown in Fig. 3.2. The period was about 8 seconds, and the amplitude was about 0.4°/sec, and swing of the model was able to be observed even by carefull looking.

As mentioned above, setting aside whether it may be said that the phenomena are truely same as those occurred in the ship, a view may be taken that fairly similar phenomena occur also in the model.

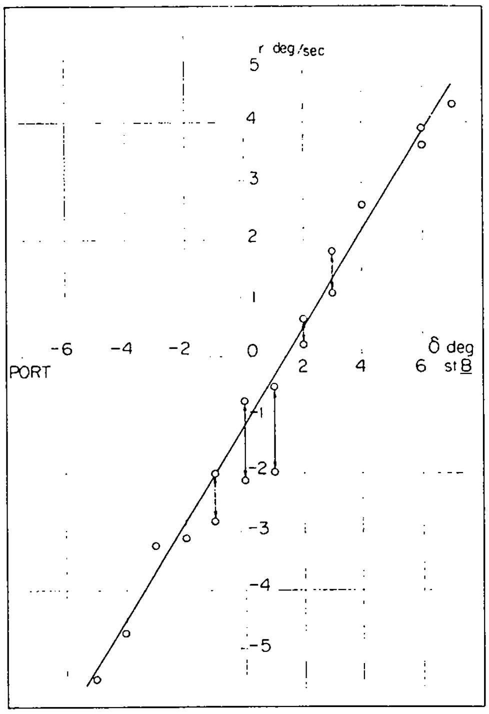

Fig. 3.1 Result of spiral tests (original model)

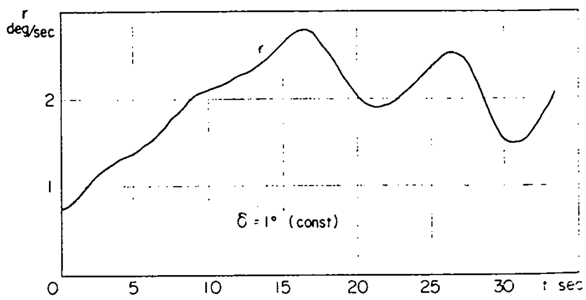

Fig. 3.2 Periodical change of yaw rate

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3.2 Effect of fin of various types

It has been known[4] hitherto that to attach fins on both sides of stern is effective to some extent as a means to prevent such abnormal phenomena. However, any theory has not been established on through what mechanism effect of the fins appears. Therefore spiral test was conducted by attaching three types of the fins shown in Fig. 3.3, taking tentative measures into consideration. The results are shown in Figs. 3.4–3.6.

Change of characteristics with respect to fin position was eye-opening. Especially in cases of Fin No. 1 and No. 2, unbelievable difference was caused by slight difference in mounting position of the fins. In case of Fin No. 1, the ship is typically unstable one, but the property is not unusual, and it may be said "gently unstable". The case of Fin No. 2 hardly differs from that of the naked

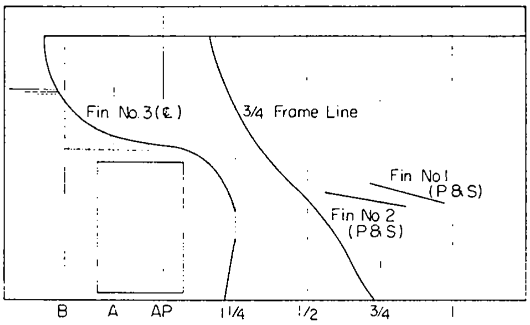

Fig. 3.3 Arrangement of fins

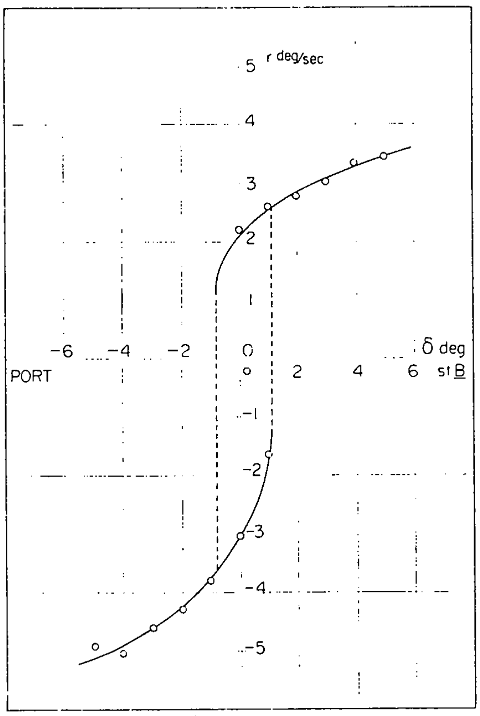

Fig. 3.4 Spiral tests (Fin No. 1)

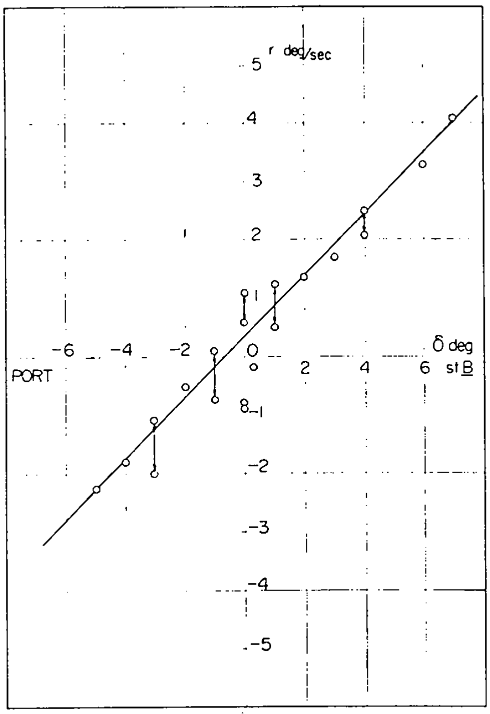

Fig. 3.5 Spiral tests (Fin No. 2)

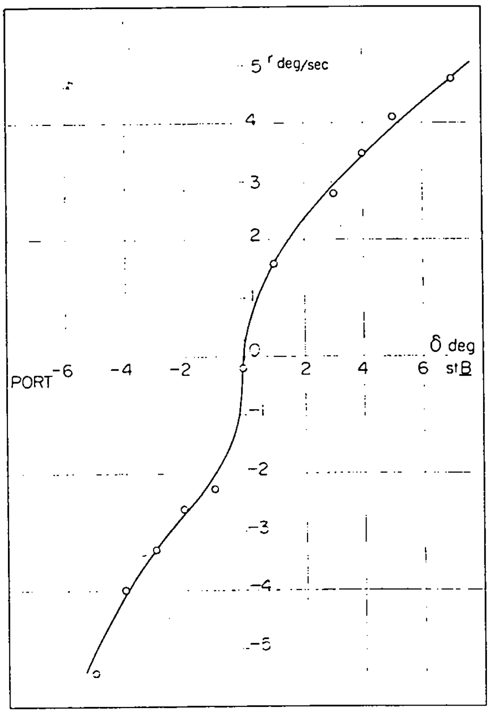

Fig. 3.6 Spiral tests (Fin No. 3)

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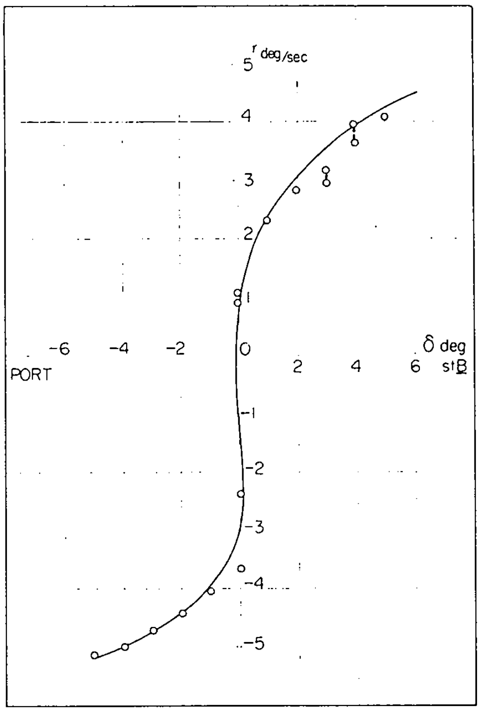

Fig. 3.7 Spiral tests (Fin No. 1 and Fin No. 3)

hull without fin, and the abnormality seems to intensify on the contrary.

The case of Fin No. 3 is within bounds of limited stability, and the abnormal phenomena seem to weaken, but asymmetry with respect to ordinate is remarkable. Usually, it is considered that the stern fins are useful for stabilization, accordingly attainment to such result may be notable. Fig. 3.7 shows result for the case of joint use of Fin No. 1 and Fin No. 3. Although plots scatter considerably in case of the rudder angle of zero, it may be said that characteristic are gentle in general.

From the experimental results stated above, it seems to be dangerous to use Fin No. 1 in practice as tentative measure, because large difference is produced in characteristics by slight change of the mounting position, though its effect is of great interest. Thus it was decided to install only Fin No. 3 tentatively on the actual ship.

4. Effect of fins in the ship

By the reason described in the preceding chapter, fins almost similar to Fin No. 3 for the model was installed on the ship, and an opportunity was found for executing a few measurements on the ship in order to investigate the effect. The results are described below briefly.

Though sharp reduction of yawing at the time of straight advance with auto-pilot was not observed, double amplitude of yawing angle was able to be restrained below about 1.5°, and obstacles against actual naviagtion seemed to be eliminated. Record of course angle during the auto-pilot was in operation is shown in Fig. 4.1. Next, as for results of spiral test shown in Figs. 4.2 and 4.3 it is not the case that fluctuation phenomena at small rudder angle vanished completely, and it remained slightly, but range of the rudder angle, in which the phenomena occurred, turned out to be very narrow, and variation of the angular velocity came to be considerably small. Consequently, relation of the

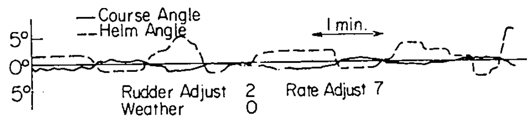

Fig. 4.1 Records of course and rudder angles when auto-pilot was used (ship with fins)

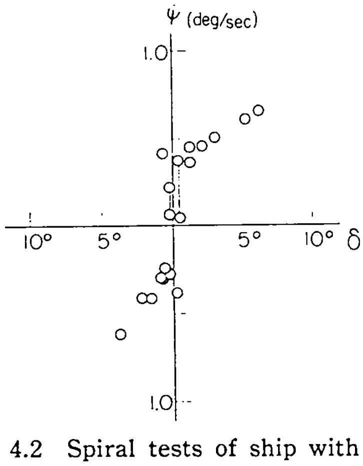

Fig. 4.2 Spiral tests of ship with fins

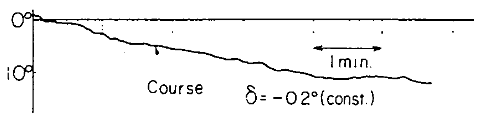

Fig. 4.3 Course records of spiral tests (ship with fin)

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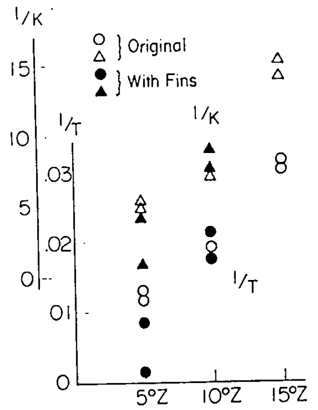

Fig. 4.4 Result of zig-zag tests (ship)

rudder angle vs. angular velocity shown in Fig. 4.2 takes form quite close to the case of ordinary ship not accompanied by the abnormal phenomena. In addition, comparison of Z test results in regard to presence of the fins is given in Fig. 4.4. Effect of the fins appears at small rudder angle, and mean course stability is reduced.

5. Analysis of the phenomena

5.1 Summarization of the abnormal phenomena

In this section, several kinematic models are presented, and explanation of various phenomena stated in the previous chapters is attemped. The abnormal phenomena to be explained are summarized as follows, for convenience of description:

(a) The measured values in spiral test of the ship often scatter at small rudder angle, and show tendency of reverse hysteresis. Moreover, they show that the ship is rather stable when the scattering points are averaged.

(b) Though rudder was fixed at small angle in the spiral test of ships, the angular velocity varied by period of about 90 seconds during turning.

(c) Direction of the turning sometimes varies during the spiral test of ship at small rudder angle.

(d) Periodical yawing motion takes place by double amplitude of 3°–5° during straight advance with auto-pilot. This motion cannot be restrained further by means of rate controll through the auto-pilot and so forth.

(e) When Fin No. 1 was installed on the model ship, and the spiral test was carried out, phenomenon of fluctuation of the angular velocity vanished, and manoeuvrability of the model showed strong "gentle instability" with loop.

(f) When Fin No. 2 was attached, the manoeuvrability of the model ship showed abnormal stable property almost similarly to the naked hull but trend that the angular velocity varied during turning intensified more than the naked hull.

(g) The fluctuation of angular velocity almost vanished when Fin No. 3 was attached, and result of the spiral test came close to the case of Fin No. 1, to extent of marginal stability.

5.2 Presentation of hypothetical model

It has been well known from long ago[2),3)] that abnormal righting moment is generated during motion at small rudder angle and stabilizes the manoeuvrability of ships, as described in this report, and it has been presumed that three-dimensional separation is the reason. Hereupon, by referring to former experiments regarding observation of flow and studies on flow around axisymmetrical bodies[5)], the following three models were considered.

5.2.1 System with abnormal moment having the origin as its center

It is assumed that abnormal moment as shown in Fig. 5.1 acts on hulls in addition to usual fluid moment. Here, M is the abnormal moment, and β represents incoming angle to aft part of the hulls. When spiral test was carried out by fixing rudder angle

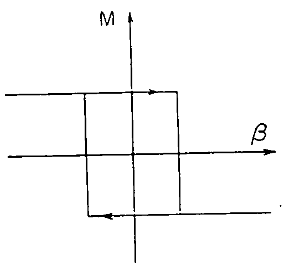

Fig. 5.1 Unusual moment

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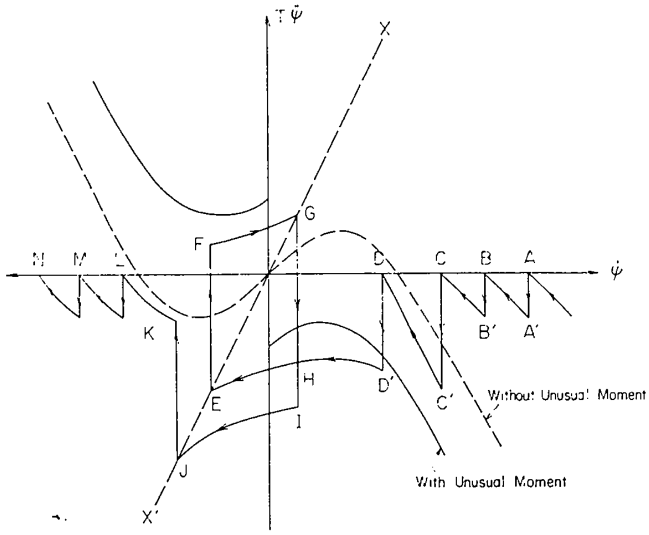

Eig. 5.2 Phase portrait at spiral test

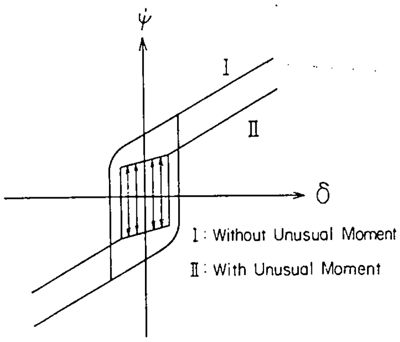

Fig. 5.3 Spiral test

under action of such abnomal moment, result as shown in Fig. 5.3 was obtained through progress as shown in Fig. 5.2. Fig. 5.2 shows phase plane, and an equation of ship motion is represented by following first order system approximation

$$T\ddot{\psi}+f(\dot{\psi})=K\delta$$

where $f(\dot{\psi})$ is turning resistance and considered to be nonlinear with respect to $\dot{\psi}$. The broken line and the solid line show relation between $\ddot{\psi}$ and $\dot{\psi}$ at zero rudder angle, and AA′BB′ shows progress by which the spiral test was carried out. It shows that steady state was not attained at the point D′ and limit cycle HEFG was formed. However, it is assumed that sign of the abnormal moment changes at the phase point on XX′. It is of interest that when mean value was taken for a part of the angular velocity variation in Fig. 5.3, the gradient of $\dot{\psi}$ to δ came to be moderated, and it resembles to said result of the spiral test of the ship.

Next, it is shown in the Appendix that there is possibility that ships sailing by application of auto-pilot make zig-zag motion, forming the limit cycle, caused by such abnormal moment.

5.2.2 System having abnormal moment origin symmetrical with respect to drift angle

In this model, the abnormal moment as shown in Fig. 5.1 originates when the incoming angle to stern is within a certain range, and result is as shown in Fig. 5.4. Also at this time, the abnormal moment is to be accompanied by hysteresis phenomenon shown in the figure.

When this abnormal moment acts on ships, course of which is originally unstable, angular velocity increases or decreases because of the instability at small rudder angle, and the limit cycle occurs on arrival at the points A and B, thus the ships make periodical motion. But there exists possibility of transition between A and B when the ships are subjected to disturbance due to wave or wind. When rudder angle is increased, and angular velocity corresponding to the rudder angle ex-

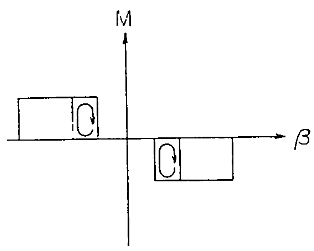

Fig. 5.4 Unusual moment which is symmetric with respect to the origin

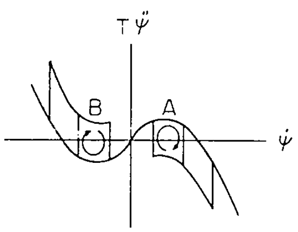

Fig. 5.5 Phase portrait with unusual moment which is symmetric with respect to the origin

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ceeds separation point, the limit cycle does not originate any more, and the ships turn at a definite angular velocity. If stabilization is attained by installation of stabilizing fins and others, abnormal phenomena do not take place, even though the abnormal moment originates.

5.2.3 System having origin symmetrical abnormal moment and periodical external force

In this model, in order or let ships make angular velocity fluctuation during spiral test or straight advance by application of auto-pilot, periodical fluid force is taken into account in addition to the non-linear moment dealt with as the abnormal moment in the preceding section. However, it is not necessary to have hysteresis especially in this case.

The phenomena (a), (b) and (c) can be explained easily with this model, similarly to the section 5.2.2. Also it can be explained as well that yawing that appears during stright advance with auto-pilot cannot be reduced by adjusting the auto-pilot, which was unable to be explained in the section 5.2.2. Reason for the latter is described briefly as follows.

Namely, value of 90 seconds for this yawing period is considerably short for the control system in view of time constant for $5°Z$ of 80 seconds, and it corresponds to frequency range in which effect of external disturbance disappears or enlarges on the contrary. Consequently, it is hardly possible to reduce the yawing by adjusting the auto-pilot, except applying rate control very strongly.

5.3 Examination of model compatibility

As mentioned above, three hypothetical models were presented to prove the abnormal phenomena, and they were examined from kinematical point of view whether the various phenomena described in the section 5.1 can be explained without any contradiction with them, and if some kinematically adaptable model exists, it is investigated on the basis of hydrodynamics further.

5.3.1 Examination based on kinematics

(1) System with abnormal moment having the origin as its center

In this case, as shown in the section 5.2.1, this model can explain reason for the phenomena (a), (b) and (d). The phenomenon (e) also can be explained, if it is assumed that separation is suppressed and the abnormal moment vanished by attaching Fin No. 1. Effects of Fin No. 3 seem to be suppression of the separation and fin effect in usual sense. Because of relative position with flow outside boundary layer, Fin No. 2 seems not to have suppressing effect against the separation, and it seems to show manoeuvrability almost similar to the naked hull. Thus, this model can explain fairly well the abnormal phenomena in general, but can not explain the phenomenon (c).

(2) System having origin-symmetrical abnormal moment

Different from the above case, hydrodynamical explanation is practical and can be accepted easily with this model, and various abnormal phenomena that take place in the spiral test of actual ship can be explained reasonably. However, as instability in the vicinity of small rudder angle is assumed, the phenomenon (d) cannot be explained, when stabilization of motion system by the use of auto-pilot is taken into account.

(3) System having origin-symmetrical abnormal moment and periodical external force

Compared with the two models stated above, this model can explain the phenomena (a) to (g) comparatively easily. Especially, it cannot help considering that it means action of some periodical external force from outside of loop of the control system that period of fluctuation during straight advance with auto-pilot does not vary with change of rudder angle ratio. Also it may be said to be suggested by the fact that the system was stable when response was determined by external force in the response test of the auto-pilot described in the section 2.1, but the limit cycle originated in self-propelling condition. Accordingly, this model, in which

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periodical external force is added to non-linear force, can explain the actual phenomena best.

5.3.2 Hydrodynamical examination of the compatible model

As described in the preceding section, it was made clear that the model given in 5.3.2 is most compatible as a model for motion, but it is necessary that non-linear righting moment and periodical fluid force originate within a certain range of incoming angle to stern. Hereupon, mechanism to generate the above forces was examined from hydrodynamical point of views.

First, concerning the non-linear righting moment, it is presumed as follows according to research on axi-symmetric bodies by Nonweiler[5]. Generally speaking, in case of slender bodies, pressure on back side is higher than that on face side behind section of maximum cross-section when angle of incidence is small. In consequence, cross-flow flows backward within boundary layer, and vertical vortexes that induce flow to stop the cross flow originate. Different from case of large angle of incidence, these vortexes affect flow on the face side, make stream-wise flow separate on face side, thus the flow as a whole separates three dimensionally at rear of the face side and discharges the vertical vortexes. At this time, pressure difference between the face side and the back side aft part of hulls is reduced because of induced velocity adverse to the cross flow, and it seems that lift is generated, in comprison with cases without vertical vortexes. In addition, the lift gives rise to stabilizing moment around center of gravity.

In the flow mentioned above, the generation of vertical vortexes and the separation of stream-wise flow cooperate, (the separation of stream-wise flow on the face side makes form of hulls asymmetric, and acts to apparenly increase effective angle of incidence and the vertical vortexes grow up to a certain extent), once such combined mechanism is initiated. Accordingly it is supposed that the vortexes are pushed fully toward the back side and abnormal moment vanishes when angle of incidence becomes large.

It is considered that hydrodynamical origin of periodical external force is that the cross flow to hulls makes unsteady flow field similar to generation of Kármán vortexes in two-dimensional flow. Considering thus, period of the unsteady flow field seems to be calculated with same Strouhal number as the two dimensional flow made by taking effective mean velocity of the cross flow. Thus, period of about 90 seconds in case of the ship can be explained in terms of order of magnitude. In addition to the above explanation, in the above model assuming the separation on the face side, flow against the cross flow is induced by the verical vortexes, but intensity of the vertical vortexes is weakened by the induced velocity, and the induced velocity becomes low, thus the vertical vortexes themselves develop again. As the vertical vortexes and their induced velocity affect mutually cyclically due to the unsteady flow field, the periodical fluid forece seems to be generated.

Next, the effect of fins is discussed. As for flow around not axi-symmetic bodies such as ships, torsion of the stream-wise flow is presumed. This seems to be related to the generation of vertical vortexes described before. Fin No. 1 was supposed to be at effective position with respect to external flow, so that the torsional flow was restrained. Furthermore, it can be considered that the fins stabilize the backward flow of cross flow in the boundary layer, and play role of preventing generation of the unsteady flow field mentioned above. It is presumed that position was not appropriate to play the role in case of Fin No. 2. Reason why Fin No. 3 acts effectively seems to be that flow field near stern was well stream-lined, and the separation of the stream-wise flow was prevented.

As mentioned above, a point at which the abnormal fluid force in this report is different from observation in the model test of a full ship is generation of periodical external force.

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and a key point is how strong the backward flow of the cross flow on face side is. It seems that shape and its variation in longitudinal direction of frame lines in the vicinity of the site where the vertical vortexes originated affect this problem.

6. Hydrodynamical examination of the models

On the hydrodynamical assumption described in the preceding chapter, a few experiments were conducted, and its adequacy was investigated.

6.1 Wind tunnel test

6.1.1 Measurement of static pressure distribution

Putting an image model of $L_{pp}=1.2$ m in Göttingen type wind tunnel, static pressure distribution around a ship hull was measured. The outlet of the wind tunnel is circular and 1.5 m in diameter, and maximum with velocity is 40 m/sec. The model has 28 holes for measuring the static pressure, and the pressure was measured with multi-tube inclined manometers or Betz's type manometers. Position of the measurement holes in the vicinity of stern is shown in Fig. 6.1. Fig. 6.2 shows outline of the pressure distribution around the ship hull. The figure 6.2 (a) corresponds to case of the naked hull and angle of incidence $\beta=0°$, and (b) to that of $\beta=4°$. The pressure on port side is indicated with white circles, and that on starboard side with black circles. Pressure difference between the two corresponding points is determined and represented as ΔP in the figure 6.2 (b). In the case of $\beta=0°$, the pressures on both port and starboard sides are equal, and in the case of $\beta=4°$, the pressure on the face side rises in front half of the ship hull, and that on the back side is higher in the rear half.

The pressure at 16 points in the vicinity of the stern, where effect of fins is supposed to be remarkable, was read by Betz's type manometers to accuracy of 0.01 mm Aq, and result as shown in Fig. 6.3 was obtained. The followings are seen from this figure:

(a) The effect of fins was mainly produced on the back side, and the pressure near cruiser stern on the face side did not vary.

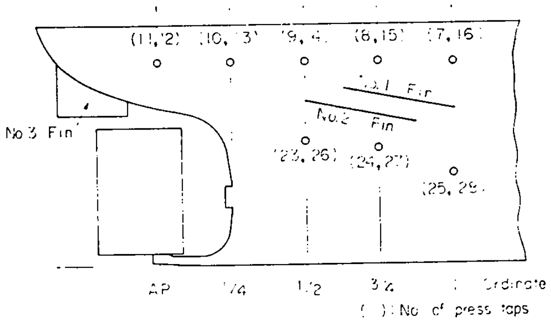

Fig. 6.1 Position of pressure taps

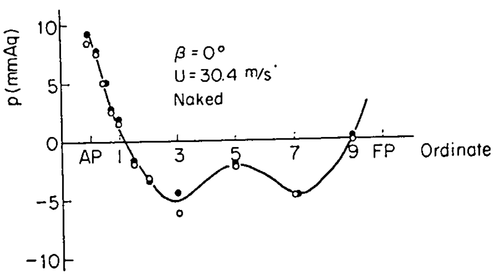

Fig. 6.2 (a) Pressure distribution around model ship (naked, $\beta=0°$)

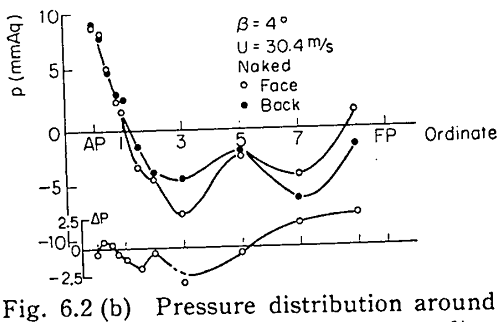

Fig. 6.2 (b) Pressure distribution around model ship (naked, $\beta=4°$)

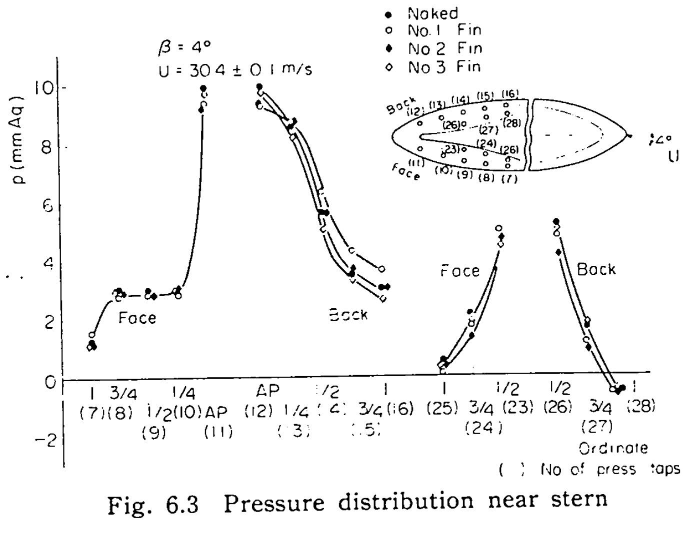

Fig. 6.3 Pressure distribution near stern

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(b) The pressure near the cruiser stern on the back side was in the order of Fin No. 1 > the naked hull = Fin No. 2 > Fin No. 3. Mean values of the pressure difference ΔP at 8 pairs of the measurement points are given below.

ΔP (naked) $=1.17$ mm Aq
ΔP (Fin No. 1) $=1.42$ mm Aq
ΔP (Fin No. 2) $=1.12$ mm Aq
ΔP (Fin No. 3) $=1.08$ mm Aq

As large pressure difference near the stern means increase or unstable moment, it can be explained that instability of manoeuvrability is increased by Fin No. 1, and that Fin No. 2 has no effect. However, rather contrary result comes out as for the effect of Fin No. 3. But the position of pressure measurement points was restricted, and further measurement must be carried out in detail to elucidate the effect of fins completely. Variation of the pressure could not be measured because of slow response of the manometer used.

6.1.2 Observation of limit stream lines

Limit stream lines around the ship hull were observed with the model described in the section 6.1.1, and elucidation of flow field was attemped. The following method was adopted to observe the limit stream lines. Oil soot was mixed in fluid paraffin and the

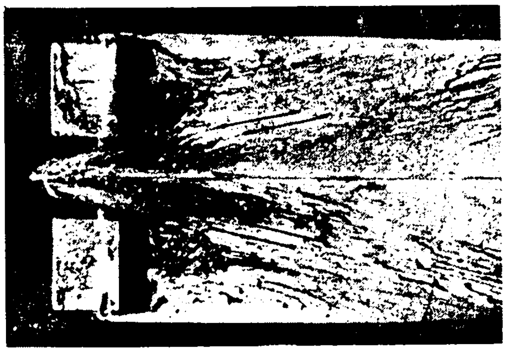

Fig. 6.4 (a) Original $\beta=4°$ face

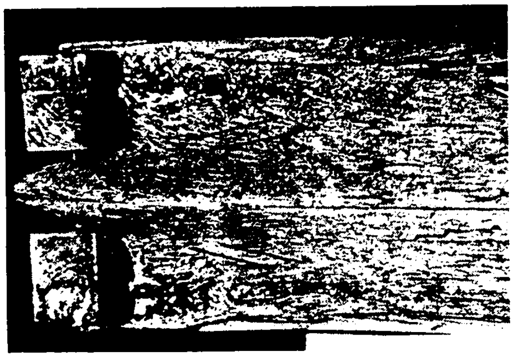

Fig. 6.4 (b) Original $\beta=4°$ back

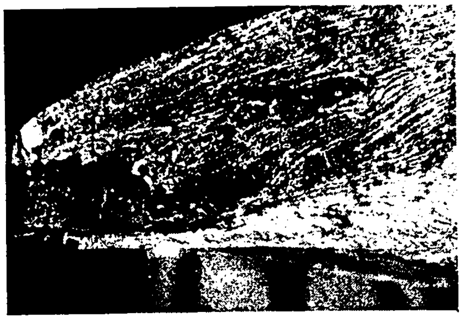

Fig. 6.4 (c) With No. 1 Fin $\beta=4°$ back

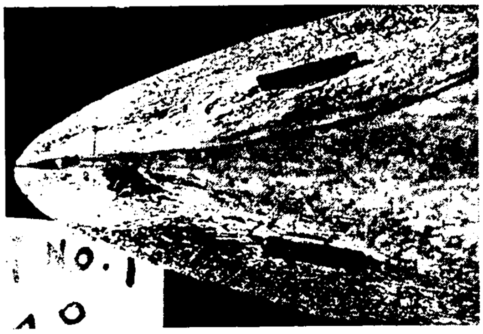

Fig. 6.4 (d) With No. 1 Fin $\beta=4°$

Fig. 6.4 (e) With No. 2 Fin $\beta=4°$

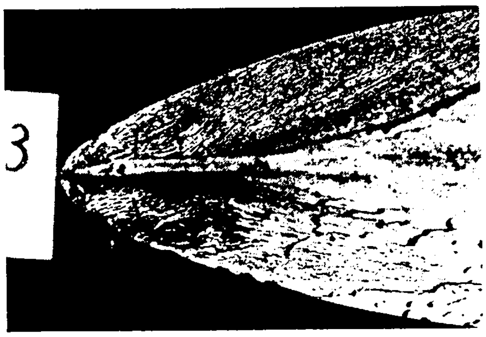

Fig. 6.4 (f) With No. 3 Fin $\beta=4°$

Fig. 6.4 Limiting streamline near stern

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mixture was painted on the hull. Wind of about 35 m/sec speed was applied for more than ten minutes. Then direction of the limit stream lines was able to be observed by white line, as shown in Fig. 6.4.

Every photograph is for the case of $\beta=4°$, and Figs. 6.4 (a) and (b) are for the face side and back sides of the naked hull respectively. Characteristic black part is found in the vicinity of the stern on the face side. It is shown that velocity gradient near surface is so small that separation is easily initiated or takes place in this part. Such separation was reported by Nomoto[3]. On the other hand, large vertical vortexes are generated on the back side, and it results in downward flow near hull surface. The fins attached on the full side has angle of incidence of 2–30° with respect to the flow. The flow on the back side in case of installation of Fin No. 1 is shown in Fig. 6.4 (c), and it is seen that the downward flow due to the vertical vortexes is restrained by the fins. Figs. 6.4 (d), (e) and (f) are the photographs for cases of installing the fins of No. 1, No. 2 and No. 3 taken from ship bottom. In every photograph, lower side corresponds to the face side, and upper side is the back side. Apparently most remarkable change due to installation of the fins appears on the face side, and flow is accelerated below the fins, and separation disappears at downstream. This effect is most remarkable in the case of Fin No. 1, and comparing Fin No. 2 and Fin No. 3 installed on the stern, effect of Fin No. 3 seems to be rather larger. This fact is similar to the result of manouvrability test stated in the chapter 3 and of great interest.

6.2 Periodical external force

As mentioned in the chapter 5, there is probability that periodical external force acts due to initiation of unstable vortexes in case of abnormal phenomena. When cause to initiate fluctuation with period of about 90 seconds, stated in the chapters 2 and 3, is attributed to such periodical external force, magnitude of the force may be about 1°–2° when it is converted into rudder angle, and seems to be within measurement error even when oblique run test is carried out. Actually, the oblique run test was attempted, but remarkable fluctuation was not observed within accuracy of the measuring instrument.

Pressure fluctuation in the wind tunnel test cannot be detected with ordinary manometers, and Betz's type manometers have deficiency that fluctuating pressure can not be measured. Thus, proof for action of the periodical external force has not been obtained. Therefore, in order to observe the vortexes at the stern, aluminium powder was scattered in a towing tank and the model was towed at a certain angle of incidence. As the result, new fact was discovered.

Namely in case of ships causing the abnormal phenomena, though particular change is not in the vicinity of the stern, wake stretches considerably periodically in a zigzag line. This is a phenomenon not found out in ordinary ships (Figs. 6.5 and 6.6), and the zigzag wake disppears when Fin No. 1 is attached. Wave length of the zigzag wake is about 5.5 m regardless of angle of incidence and ship speed. The wave length divided by the ship speed comes out to be 6 seconds, and value of about 8 seconds for meandering period of the model ship described in the chapter 3 seems to be in good agreement in view of order, therefore it should regarded that it is closely related to the abnormal

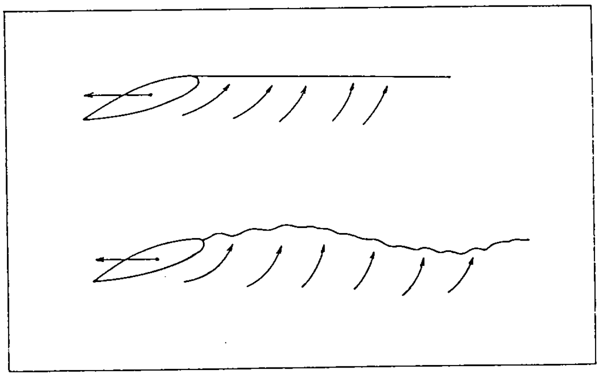

Fig. 6.5 Comparison of wakes of usual ship (upper side of figure) and ship affected with unusual moment (lower side)

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Fig. 6.6 Unusual wake

phenomena.

In view of the experiments mentioned above, is should be considered that some periodical external force acts as a part of the abnormal phenomena through the vortexes and so forth, since abnormal wake originates in the model run obliquely under some restraint.

6.3 Examination

Presuming cross flow of the naked hull form observation of the limit stream lines near the stern described in the section 6.1, it comes to be as shown in Fig. 6.7. It is like the flow around axi-symmetric bodies previously stated in the section 5.3.2. When fins are attached, the vortexes stretching vertically to the flow is suppressed, and the effect is large on the back side especially, accordingly static pressure at upstream of the fins turns out to rise.

Also as for periodical fluid force, it is more probable that the periodical fluid force is caused interaction of the flow due to the

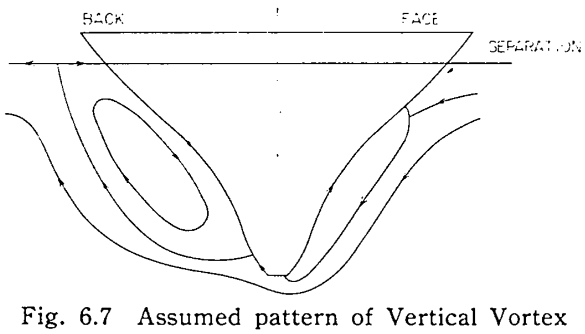

Fig. 6.7 Assumed pattern of Vertical Vortex and Cross Flow

vertical vortexes on the face side and the cross flow than due to Kármán vortexes among those discussed in the chapter 5. This consideration is supported by the facts that the zigzag wake described in the preceding section is remarkable on the face side, and the period is independent of angle of incidence. Furthermore, the fins mounted on suitable position seems to rectify this opposite flow and to have capability of stabilizing flow field.

7. Conclusion

As for the ship which showed the abnormal phenomena of manoeuvrability listed in the section 5.1 in the ship and model experiments, it was found that the phenomena can be explained in outline from kinematic point of view by assuming the following hydrodynamical model. In addition it was confirmed that this model can be accounted for also hydrodynamically through model basin test and wind tunnel experiment.

First, as for the assumed model, the followings are concluded.

(1) This ship is originally course-unstable unless there is abnormal flow such as separation.

(2) Though the abnormal fluid force does not initiate within range of quite small drift angle abnormal flow is generated suddenly in the vicinity of stern when the drift angle exceeds a certain limit, consequently counter-moment in direction of decreasing unstable moment is generated. The counter-moment is origin-symmetric with respect to the drift angle. It is considered that the abnormal flow is the vertical vortexes caused by cross flow and separation on the face side induced by the vortexes.

(3) Owing to growth and vanishing of the abnormal flow, periodical moment is caused. The magnitue is about 1° as converted into rudder angle, and the period is bout 90 seconds in the ship.

Useing the above model, the abnormal phenomena can be explained as follows.

(4) Because of the course instability, the

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ship cannot advance straight, and starts to turn. Though the turning was stabilized at a certain angular velocity because of the abnormal moment of (2) and the ship begins steady turning but yawing takes place at period of about 90 seconds due to the periodical moment mentioned in (3). In addition, direction of the turnning is varied by slight disturbance, and steady turning is started at a stability point on the opposite side, according the ship yaws while turning. This phenomenon occurs in case of rudder angle of 1–2° as well. When the course is considered in terms of averaged fluctuation, course of the ship comes to be stable. (See the explanation of (a), (b) and (c) of 5.1.)

(5) Period of the periodical abnormal moment is about 90 seconds, and is too short to be suppressed by auto-pilot, and limit cycle of nearly same period is originated. Accordingly, it is expected that period of the limit cycle hardly varies even when rate of rudder angle of the auto-pilot is changed, and rate control is not so effective, and these facts agree well with actuality.

(6) Horizontal fins of type No. 1 attached to stern as shown in the section 3.2, suppress generation of the vertical vortexes on the back side, and stabilizes those on the face side. Consequently, limit drift angle to cause the abnormal moment is increased, and the ship recovers property of original "gentle course instability". (See the explanation of (e).)

(7) Longitudinal and vertical position of the fins is delicate, and effect of Fin No. 2 a little behind and below Fin. No. 1 is nearly same as that of the naked hull or rather promotes the abnormality. (See the explanation (f).)

(8) Fin No. 3 attached to stern center plane acts to broaden a little the limit of originating the abnormal moment. In consequence, despite the center plane fin with usual stabilizing effect only was installed, the ship became more unstable than the naked hull. (See the explanation of (g).)

As mentioned above, explanation can be made to some extent, yet there are many unknown points. Especially in observation of stream lines, thoroughly that effect of the fins appears remarkably on the face side, on the other hand, pressure variation hardly occurs on the face side, and is more remarkable on the back side.

Furthermore, it cannot be explained that despite longitudinal position and vertical position of Fin No. 1 and No. 2 do not differ much, there is eye-opening difference in their effect. This seems to affect probably very local change in shape of the ship largely separation phenomenon, but these are problems to be elucidated hereafter.

At the end of this report, the authors offer their cordial thanks to Professor Nomoto of Osaka University for his useful discussion from initial stage of the present study, and to Kinkai Yusen Co. Ltd., Setoda Zosen Co. Ltd. and Tokyo Keiki Seizosho for lending understanding and convenience for carrying out the ship test.

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Appendix

Examination concerning the limit cycle of auto-pilot ship

1. Equation of motion

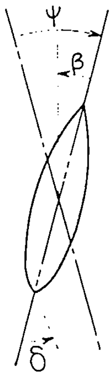

Fig. A.1 Coordinates

By denoting the abnormal moment by M, equations of motion for ships are

$$\left.\begin{aligned} A\ddot{\psi}+B\dot{\psi}+C\beta&=D\delta+M \\ a\dot{\beta}+b\beta+c\dot{\psi}&=d\delta \end{aligned}\right\} \quad \text{(A-1)}$$

where

$$\left.\begin{aligned} &A=n\left(\frac{L}{V}\right)^2, \quad B=C_{M\omega}\left(\frac{L}{V}\right), \\ &C=-C_{M\beta}, \quad D=C_{M\delta} \\ &a=m_Y\left(\frac{L}{V}\right), \quad b=C_{Y\beta}, \\ &c=-(m_x-C_{Y\omega})\left(\frac{L}{V}\right), \quad d=C_{Y\delta} \end{aligned}\right\} \text{(A-2)}$$

Eliminating β from the two equations of (A-1), the following relation is obtained.

$$\begin{aligned} &T_1T_2\dddot{\psi}+(T_1+T_2)\ddot{\psi}+\dot{\psi} \\ &=K\delta+KT_3\dot{\delta}+\frac{a}{bB-cC}\dot{M}+\frac{b}{bB-cC}M \end{aligned} \quad \text{(A-3)}$$

where T_1, T_2, T_3 and K are given usually.

2. Necessary condition of the limit cycle

It is assumed that auto-pilot given by

$$-\delta=K_1\dot{\psi}+K_2\psi \qquad \text{(A-4)}$$

is applied in equation (A-2). At this time, carriying out first order system approximation, the following expression are resulted.

$$\left.\begin{aligned} &\ddot{\psi}+\left(\frac{1+KK_1}{T}\right)\dot{\psi}+\frac{KK_2}{T}\psi=\frac{M_1}{T}\dot{M}+\frac{M_2}{T}M \\ &M_1=\frac{a}{bB-cC}, \quad M_2=\frac{b}{bB-cC} \end{aligned}\right\}$$

(A-5)

Below, assuming conformity with consideration of equivalent linearity, M is assumed as sinusoidal function.

By putting right hand side of (A-5) as M_E and denoting phase of arbitrary function F by $\arg F$,

$$\left.\begin{aligned} &\arg M_E=\arg M+\alpha \\ &\alpha=\tan^{-1}\frac{M_1\omega}{M_2}=\tan^{-1}\frac{a\omega}{b}=\tan^{-1}\frac{m_Y\omega'}{C_{Y\beta}} \end{aligned}\right\}$$

(A-6)

and the amplitude is expressed as

$$\text{amp.}\,M_E=\sqrt{\left(\frac{M_1\omega}{T}\right)^2+\left(\frac{M_2}{T}\right)^2}\cdot\text{amp.}\,M$$

(A-7)

In order that the equation (A-5) has periodical solution, M_E must have a component of same phase as $\left(\frac{1+KK_1}{T}\right)\dot{\psi}$. In case of $\frac{1+KK_1}{T}<0$, M is not necessary to produce the limit cycle, as there exists non-linear damping term.

Present object of interest is to obtain necessary condition for producing the limit cycle in case of $\frac{1+KK_1}{T}>0$. If it is assumed that

$$\arg M=\arg\dot{\psi}+\delta \qquad \text{(A-8)}$$

the following relation

$$\frac{\pi}{2}>\alpha+\delta>-\frac{\pi}{2} \qquad \text{(A-9)}$$

shonld hold in order that M_E has a same component as $\dot{\psi}$.

3. Relation between $\dot{\psi}$ and β

Before considering the equation (A-9) definitely, relation of phases of $\dot{\psi}$ an β is made clear. By putting

$$\begin{aligned} &\dot{\psi}=\dot{\psi}_0\cos\omega t \\ &\beta=\beta_0\cos(\omega t+\varepsilon), \quad \pi>\varepsilon>-\pi \end{aligned}$$

we obtain

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$$\left.\begin{aligned}\cos\varepsilon&=\frac{K_2da\omega-\omega bc+bK_1d\omega}{P^{1/2}}\\ \sin\varepsilon&=\frac{a\omega^2c+a\omega^2K_1d+K_2db}{P^{1/2}}\\ \beta_0&=\frac{P^{1/2}K_2}{K_2(a^2\omega^2+b^2)+2abK_1\omega^2}\\ P&=\sqrt{(K_2da\omega-\omega bc+bK_1d\omega)^2+(a\omega_2c+a\omega^2K_1d+K_2db)^2}\end{aligned}\right\}\qquad\text{(A-10)}$$

Phase characteristics of the equations (A-10) are controlled by value C.

4. Phase of external force

(a) Case of origination of abnormal righting moment in relation to $\dot{\psi}$.

When hysteresis is taken into account, phase lag of $\alpha_{\dot{\psi}}$ is expected $\left(\frac{\pi}{2}\geqq\alpha_{\dot{\psi}}>0\right)$. Accordingly.

$$\delta=-\alpha_{\dot{\psi}}+\pi\qquad\text{(A-11)}$$

hold, and the equation (A-9) cannot be statisfied. Hence the abnormal moment originated at the phase of $\dot{\psi}$ cannot produce the limit cycle, even when the hysteresis is taken into account.

(b) Case of origination of the abnormal righting moment in relation to β

As there exists phase delay of α_β when the hysteresis is considered,

$$\delta=\varepsilon-\alpha_\beta\pm\pi$$

holds, and substituting into (A-9) and taking $\pi-\alpha\geqq\varepsilon$ into account, when

$$\pi-\alpha>\varepsilon>\frac{\pi}{2}-\alpha+\alpha_\beta\qquad\text{(A-12)}$$

holds, possibility of the limit cycle exists.

From above consideration we know that when

$\alpha_\beta\to0$,

$\alpha\to$large, or $\omega' m_Y\gg C_{Y\omega}$,

$c\to$large,

limit cycle trends to generate. We can also see in Fig. A.2 that the situation is not able to be improved by $K_1\to$large under the said conditions.

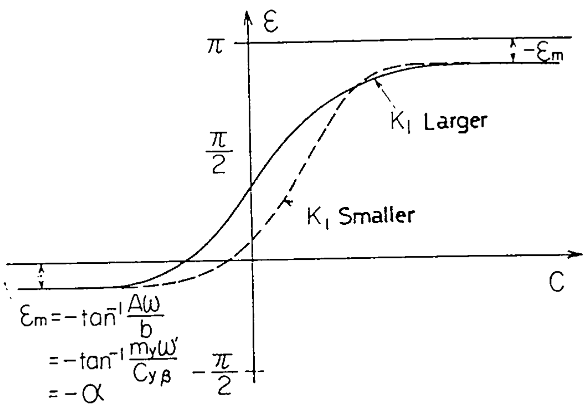

Fig. A.2 ε as a function of coefficient of C

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