7. On the Unusual Phenomena in Manoeuvrability of Ships

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Summary

It has been passed more than ten years since so-called unusual phenomena in manoeuvrability were first reported by Nomoto[1]). At the early stage of research, the phenomena were regarded as the unusual scale effect, because it appeared only in model ships. According to the tendency of growing in fullness of ships, however, these phenomena have been observed on real ships.

For these several years the authors have treated such phenomena appeared on either model ships or real ships frequently in free-running tests, captive model tests or full-scale trials. Some of these results were already published[2]),[3]).

Through the detailed examination of these experiences, the comprehensive explanation of the phenomena is made as the main purpose in the present paper.

It is known from the captive model tests that in model ships with the phenomena the measured hydrodynamic force contains two kinds of forces: one is the ordinary force proportional to ship motions and the other is the unusual force which appears only in ships with the phenomena. This unusual force is found to originate from the flow separation at one side of the stern by the flow observation. The unusual force is roughly classified into two types; binary type and breakline type (see Fig. 5).

Another factor closely related to the phenomena is directional stability of ships. Almost all the unusual phenomena ever found are shown to be well explained by the combinations of directional stability with two types of unusual force.

1. Introduction

It was more than ten years ago when Nomoto[1]) first reported so-called unusual phenomena in manoeuvrability. At those days ships became fuller and beamier extremely. He carried out model ship experiments, being afraid that the ship had inferior manoeuvrability. But the result was to the contrary. The model ship happened to be super-stable. Generally it has been believed that the fuller and beamier ships become, the poorer course stability they show. It is the reason why these phenomena are called unusual phenomena or unusual stable. Another expression is unusual scale effect[1]), because the phenomena mainly appeared in model ships and real ships behaved as unstable at those days.

From that time on we have heard of many cases in further fuller ships which behave quite strange. Some of them are, for example, the ship which has two characteristics in steady turning[2]), the ship which oscillates starboard and port alternatively under the helm amidship[3]), the ship which has so-called "double-loop" steady turning characteristics[4]) etc. They are also called unusual phenomena.

It is very important to clarify the mechanism of unusual phenomena, because the phenomena cause troubles not only in manoeuvrability itself but also in studies of manoeuvrability; *e.g.*, on scale effect and on relation between ship particulars and

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her manoeuvrability. At the same time, the phenomena are often accompanied with fluctuation in self-propulsion factors, which disables us from the power estimation. In the field of ship resistance and propulsion, this fluctuation is called unstable phenomena and is still under discussion.

There are already many researches concerning to the unusual phenomena. The authors, for instance, have studied the cases of a fishery research vessel3) and an ore carrier2). Most of such researches, however, couldn't reach inclusive conclusions, because the phenomena contain a wide variety.

Motora, Takagi *et al.*5), and Motora and Fujino6) have tried to explain the phenomena inclusively. Although at those days few data concerning to the phenomena were available, they introduced the concept of "unusual moment" due to "asymmetric flow separation at the stern", and tried to make the phenomena clear. Even now these papers are still suggestive.

The present study is to explain the phenomena ever reported as inclusively as possible, on the base of our long experience; captive model tests, observations of stern flow, free-running tests of both real ships and model ships. First, we show that on ships with the phenomena unusual hydrodynamic force acts due to flow separation at the stern as well as ordinary hydrodynamic force. The unusual force is nearly constant against ship motions, though the ordinary force is proportional to ship motions and helm. Then we explain the state of the stern flow which causes the unusual force and classify this unusual force into two basic types. Lastly, we confirm that almost all types of the unusual phenomena ever reported can be reasonably explained by the combinations of the unusual hydrogynamic force with the ship's own course stability.

2. Hydrodynamic Force and Stern Flow in the Case of Ships with Unusual Phenomena

As have been mentioned above, the unusual phenomena seem to appear in various ways. For example, let us suppose two model ships. The results of free-running tests of these model ships are seemingly different, so that we are apt to regard the unusual phenomena of them are essentially different. But, carrying out captive model tests, the character of measured hydrodynamic force is not so different between them. How can we explain the reason? According to the test results of Planar Motion Mechanism (PMM) in Hiroshima University, the unusual hydrodynamic force of ships with unusual phenomena seems to be classified into two types; binary type and breakline type. In the followings, we introduce the two types of unusual force and the stern flow which causes the unusual force.

2.1 Hydrodynamic Force and Stern Flow of Ships Acting Binary-Type Unusual Force

Fig. 1 shows yaw-moment about C.G. obtained by oblique towing tests of the fishery research vessel and the ore carrier respectively. Other details of experiments such as lateral force may be referred the papers2),3). Here we describe the fundamental character of these hydrodynamic forces.

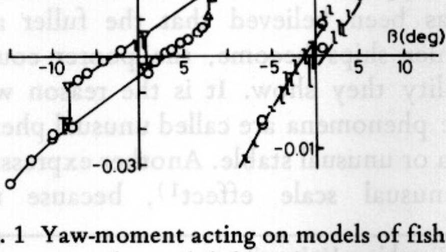

Fig. 1 Yaw-moment acting on models of fishery research vessel (left) and ore carrier (right) towing obliquely

We can point out that the measured hydrodynamic force doesn't settle into one line but obviously divided into two lines. Besides, the difference between the two lines is nearly constant against the change of drift angle. Though both model ships are common at these points, there is some qualitative difference. In the case of the fishery research vessel, measured force is well-settled and hysteresis can be obviously observed, when varying drift angle slowly. On the other hand, in the case of the ore carrier, the measured values shift from one line to the other almost at random and, besides, each value fluctuates even on one line.

Then let us proceed to the flow observation. Nomoto, who reported the unusual phenomena at first, pointed out that flow separation occurred at the face side of the stern. Flow observation was held at various institutes after then and is confirming the Nomoto's indication. Fig. 2 is the result of flow observation around the stern surface of the fishery research vessel. Visualization was done by very small air bubbles. This figure shows the case of 4° starboard drift angle. The strong lateral flow over the propeller and the rudder and the distinct flow separation at the face-side stern near water surface are impressive. In the case of the ore carrier, as reported before[2]), the flow is similar with this. These investigations can be summarized as follows.

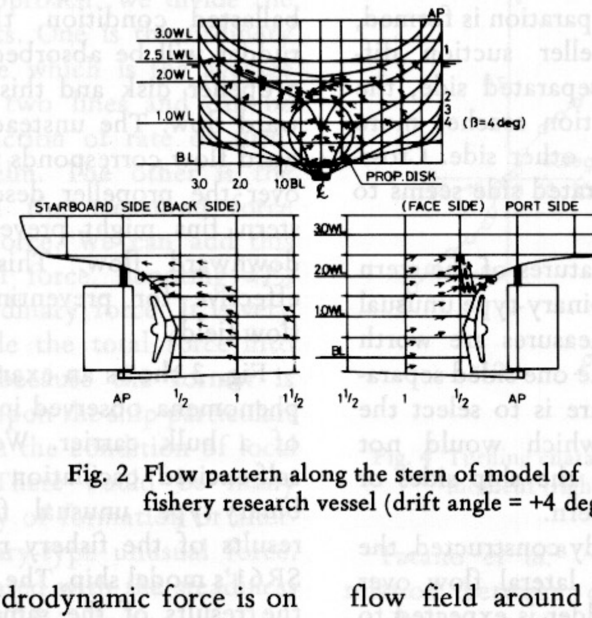

Fig. 2 Flow pattern along the stern of model of fishery research vessel (drift angle = +4 deg)

1) When the hydrodynamic force is on the turning characteristics of upper line in Fig. 2, flow crosses laterally from starboard to port over the propeller or the rudder and flow separation generates at the port-side stern near water surface. In the case of on the lower line, vice versa.

2) This flow separation develops from unstable flow field around the upper stern. Flow from both sides or bottom into the upper stern is insufficient and the flow field around here becomes unstable. Bluntness of the upper part of the stern and strong propeller suction cause this.

3) Once the lateral flow over the propeller or the rudder is created, the unstable flow field grows to the flow separation at one side of the stern. The separation occurs at either side of the stern, but face-side separation occurs more easily. Generation of the lateral flow is affected by the aperture size over the propeller

or the rudder and the flatness of the stern bottom. When the clearance is large enough, the separation is seldom affected by the direction of propeller revolution. But the narrower the clearance becomes, the easier starboard-side separation does occur in cases of clockwise-revolution propellers.

4) The direction of the separation is affected by steering and in many cases by steering the separation occurs easily at the side where the steering effect would decrease.

5) The change of drift angle doesn't make the separation point shift. This corresponds to the fact that the difference between two turning characteristics is almost constant against the change of drift angle.

6) When one-sided separation is formed, the strength of propeller suction differs at two sides. At separated side, the region of propeller suction reaches more upstreamward than the other side. Cross-flow from the non-separated side seems to fill up the difference.

These facts are the features of the stern flow field which causes binary-type unusual force. Several countermeasures are worth considering to prevent the one-sided separation. The radical measure is to select the suitable frame lines which would not obstruct the flow from the ship sides or bottom into the upper stern.

When the ship is already constructed, the centre fin shutting the lateral flow over the propeller or the rudder is expected to be effective. However the centre fin is to prevent the one-sided separation, it would not extinguish the unstable flow field around the upper part of the stern and some fluctuation may sometimes remain in the hydrodynamic force.

The above discussions are for cases in full-loaded or nearly full-loaded condition. The unusual phenomena would occur even in ballasted condition. Tagano and Asai[7] observed the "downward stream (flow)" into the propeller in ballasted condition of the model ship which was used in the research project of SR61 (Research Committee No. 61 of the Ship Research Association of Japan). From the point of manoeuvrability, the downward flow itself would not play an important role, but it is more important to consider the unbalanced flow field in both ship sides caused by the downward flow. They observed also the remarkable asymmetry in pressure distribution along the hull. This suggests us there was the similar flow field with the one reported here. They set several kinds of stern fins. These fins are likely to have the similar effect with the centre fin[2],[3] applied by the authors. In ballasted condition, the flow over the rudder will be absorbed reversely into the propeller disk and this will be the downward flow. The unsteadiness of the downward flow corresponds to that of flow field over the propeller described above. Their stern fins might prevent to generate the downward flow. This means they are effective for preventing the asymmetric flow field.

Fig. 3 shows an example of the unusual phenomena observed in the trial condition of a bulk carrier. We can observe the self-excited oscillation and recognize the binary-type unusual force, just as the results of the fishery research vessels and SR61's model ship. The figure also indicates the results of the same ship after fitting the centre fin. Though the phenomena itself remains, it recovers well and the centre fin is found to be effective. Since the centre fin is a vertical plate, it is not effective for preventing the downward flow. It only prevents the asymmetric stern flow. These examples show the unusual phenomena would appear even in ballasted condition.

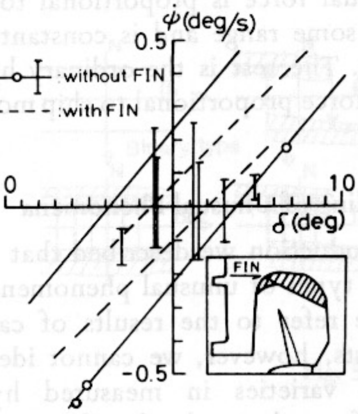

Fig. 3 Turning characteristics of bulk carrier with and without centre fin

Next let us consider the description of the hydrodynamic force acting on these ships. As a first approach, we divide the force into two parts. One is the ordinary hydrodynamic force which is the average of two values on two lines and can be expressed as a function of rate of turn, drift angle and helm. The other is the difference between the measured force and the ordinary force. We can add this binary-type unusual force, denoting $\pm Y_a$ and $\mp N_a$, to the ordinary force. It is very convenient to divide the total force into these two terms, because the former is roughly dependent upon the ship particulars and the latter upon the condition of local flow separation. There could be many variation in the way of formation or alternation of the binary-type unusual force. The variation is related with the steadiness of the stern flow field including the flow separation. Fig. 1 shows the case where the hydrodynamic force has hysteresis and the case where it shifts from one line to the other at random.

2.2 Breakline-Type Unusual Force

As have been described in Introduction, there is a type of unusual phenomena where manoeuvring characteristics within small ship motions is super-stable. Fig. 4(A) is the turning characteristics of a small tanker and it corresponds to this type. There is no fluctuation within small rudder angle and it shows ideal turning characteristics.

Fig. 4(B) is yaw-moment of the tanker model obtained from oblique towing tests. In the case of this model, hydrodynamic force is not divided into two values nor fluctuant. The line is broken within small drift angle. Although binary-type unusual force is easy to connect with manoeuvring troubles, this breakline type turns the matter better: the ships will be super-stable. In this meaning we distinguish these two types each other.

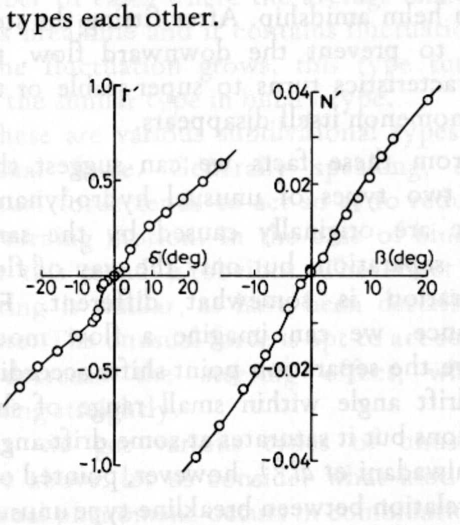

Fig. 4 Turning characteristics (left) and yaw-moment (right) of model of small tanker

Tatano *et al.*[8)] pointed out the close relation between course stability within small ship motions and the aperture size over the propeller or the rudder. The narrower the clearance is, the poorer the course stability becomes. They revealed this fact from results of free-running tests of many full-bodied ships. This is contrary to the data of fine ships. From this fact, the breakline-type unusual force seems to be related with the lateral flow crossing this clearance.

It was not so clear but the lateral flow crossing the clearance above the propeller was observed by the flow observation of the tanker model. But, as the phenomenon is very gentle, it was not possible to confirm the flow field completely as in the case of binary-type unusual force. Then the centre fin was fitted and oblique towing tests were conducted to certify if the lateral flow exists or not. The breakline characteristics disappears and it is verified that the similar flow exists with the case of binary-type unusual force.

Similar results were given in the report of Tagano and Asai[7]. The SR61's model originally shows self-sustained oscillation with helm amidship. After fitting the stern fins to prevent the downward flow, the characteristics turns to super-stable or the phenomenon itself disappears.

From these facts we can suggest that the two types of unusual hydrodynamic force are originally caused by the same flow separation, but only the way of flow separation is somewhat different. For instance, we can imagine a flow model where the separation point shifts according to drift angle within small range of ship motions but it saturates at some drift angle. Kashiwadani *et al.*[9], however, pointed out the relation between breakline-type unusual force and bilge vortices of blunt stern, so we cannot conclude at this moment. The authors also observed the urgent change in bilge vortices by small change of drift angle in the tests of the fishery research vessel and the ore carrier. But direct relation between the bilge vortices and the unusual phenomena couldn't be recognized in these models. Anyway, it should be still considered in the future concerning the relation between the bilge vortices and manoeuvrability.

The description of this breakline-type hydrodynamic force can be regarded similarly with the case of binary-type. The unusual force is proportional to drift angle to some range and is constant over the range. The rest is the ordinary hydrodynamic force proportional to ship motions and helm.

3. Modelling of Unusual Phenomena

In Introduction we described that there are many types of unusual phenomena. As far as we refer to the results of captive model tests, however, we cannot identify so many varieties in measured hydrodynamic force, but only classify two basic types as mentioned in the previous section. From the fact, it is understandable that we should consider not only the behaviour of unusual force but also another factor to clarify the varieties of unusual phenomena. As this factor, we should first choose course stability which takes an important role in manoeuvrability of full-bodied ships.

It is a premise that the hydrodynamic force acting on the ships with unusual phenomena can be composed of the ordinary force and the unusual force. The former is proportional to ship motions and helm and the latter is caused by flow separation at the stern. Then we can derive various models of unusual phenomena, combining the types of unusual force with course stability.

First we consider about the types of unusual force. It is obvious from the conclusion of the previous section that the two basic types are binary type and breakline type. From these two basic types we can make various subdivisional types as shown in Fig. 5. The ordinate denotes the unusual moment (the pattern is same with the unusual force, though the sign is opposite), and the abscissa means the apparent drift angle at the stern: $\beta_S(=\beta+0.5r')$. Though in the following discussions we assume the unusual force (moment) is governed by this apparent

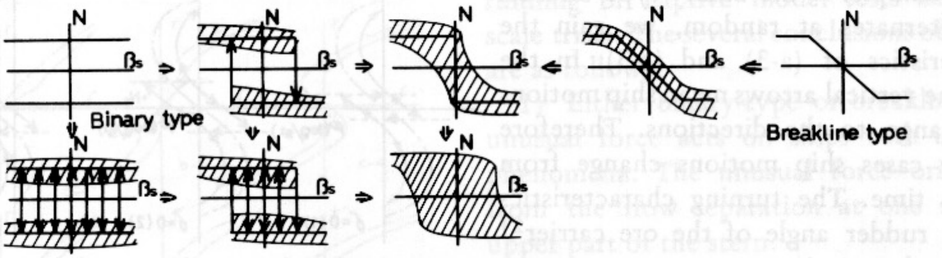

Fig. 5 Basic patterns of unusual moment

drift angle β_S, steering also affects in fact.

When we compose the subdivisional types, we should take account of the way of alternation of the flow separation and the unsteadiness of the flow field itself, which are described in the previous section. In the case of binary-type unusual force, there are two subdivisional types: one is the case where hydrodynamic force alternates with hysteresis and the other is the case with random alternation. In the figure the mark ↑ means hydrodynamic force alternates to the direction of the arrow and the mark ↕ means it alternates to both directions. We can consider further type where hydrodynamic force alternates with hysteresis and besides within the hysteresis it changes at random. This type can be regarded as the usual form of the random type.

The hatched region in the figure means hydrodynamic force fluctuates within the region because of the unsteadiness of the flow field. There may be some types in the way of fluctuation. We observed the case where it fluctuates sinusoidally and the case where no regularity is recognized. If the region of fluctuation grows extremely, it becomes another type where hydrodynamic force never settles within small ship motions.

In the case of breakline-type unusual force, there is a case where seldom fluctuation is observed. This type improves manoeuvrability. But, there are not small number of cases where the average character is breakline and it contains fluctuation. If the fluctuation grows, this type turns into the similar type in binary type.

These are various subdivisional types in unusual force. Generally speaking, the unusual force tends to act so as to reduce the turning motion. In the case of binary type this trend is obvious. The effect of steering is similar, as have been described before. The unusual force is apt to act so as to decrease the steering effect, when running straightly.

As we get various types of unusual force above, let us consider what kind of unusual phenomena occurs in combinations with course stability. In the following considerations, we mainly treat the turning characteristics which expresses the ship's manoeuvrability typically.

Fig. 6 shows the various turning characteristics where binary-type unusual force acts. The chain line in the figure shows the turning characteristics without unusual force and the full lines denote the combined result with unusual force.

The left row is the case of stable ships and the right is the case of unstable ships.

If typical binary-type unusual force acts, two steady turning curves are completely observed, as in (a-1) and (c-1). The model ship of the fishery research vessel[3)] is this example. If the binary-type unusual force alternates at random, we gain the characteristics of (a-3) and (c-3). In the figure the vertical arrows mean ship motions may change to the directions. Therefore in these cases ship motions change from time to time. The turning characteristics at large rudder angle of the ore carrier[2)] corresponds to (c-3).

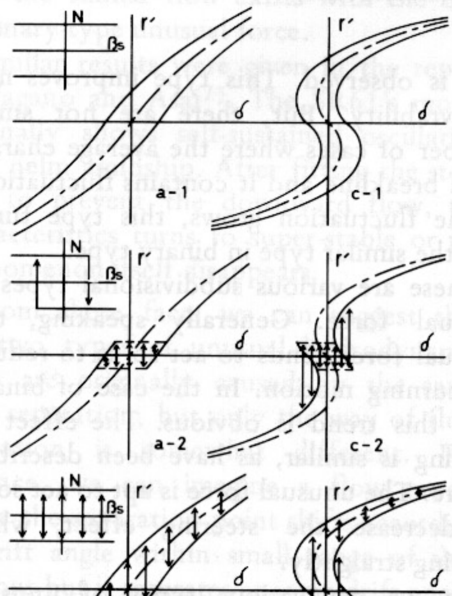

Fig. 6 Schematic diagrams of turning characteristics under combinations of directional stability with unusual moment (binary type)

The turning characteristics accompanied with binary-type unusual force with hysteresis is (a-2) and (c-2). When ship motions reach the broken lines, the flow separates at the other side of the stern and the sign of unusual force changes. Fig. 7 shows the details of this case in the form of phase plane trajectory. Case (1) explains that the

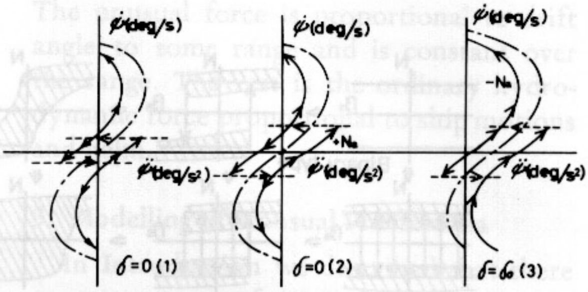

Fig. 7 Schematic diagram of phase plane trajectory under combinations of directional stability with unusual moment (binary type: c-2)

self-sustained oscillation occurs with the helm amidship but in case (2) the motion reaches either starboard or port steady turning, even if the helm is amidship. If, for example, starboard helm is commanded, only starboard steady turning remains as shown in case (3). The chain line is the trajectory without unusual force.

Fig. 8 shows turning characteristics accompanied with breakline-type unusual force. The chain lines represent the characteristics without unusual force and correspond to stable, marginal stable and unstable characteristics from the left respectively. In the figure, (a-4), (a-5), (b-4) and (b-5) are characteristics of so-called unusual stable. The small tanker in the present paper is an example of (b-5).

In cases of (b-4) and (b-5), the turning characteristics jumps at a pair of rudder angle. This is not because of discontinuity in unusual force but because of the characteristics of marginal stable ships. In marginal stable ships, the damping force is nearly constant against the change of turning motion at small ship motions. Therefore small variation in hydrodynamic force results in large difference in steady turning.

The apparent glance at (c-4) looks like marginal stable. But this is due to the balance of negative damping and unusual force. Double-loop characteristics reported

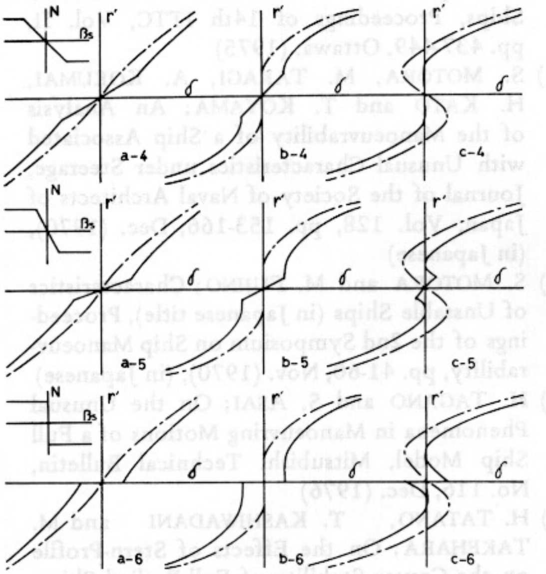

Fig. 8 Schematic diagrams of turning characteristics under combinations of directional stability with unusual moment (breakline type)

by Fujino (referred by Wagner Smitt[4]) is represented in (c-5).

The intermediate cases of binary-type unusual force with hysteresis and breakline-type unusual force are (a-6), (b-6) and (c-6). Abrupt change in unusual force cancels the turning force by steering, so that the helm acts nothing within some range of rudder angle.

Above discussions enable to explain quite many types of unusual phenomena by the combinations of two basic types of unusual force with course stability. Besides, almost all cases of unusual phenomena ever reported can be further covered with consideration of various types of fluctuation in unusual hydrodynamic force due to unsteadiness of flow field.

4. Concluding Remarks

The present paper was aimed at explaining the unusual phenomena as inclusively as possible from the long experience of free-running or captive model tests and full-scale trials. The several conclusions obtained are as follows:

1) Either binary-type or breakline-type unusual force acts on ships with unusual phenomena. The unusual force originates from the flow separation at one side of upper part of the stern.

2) Combining two basic types of unusual force with course stability of ships, quite various types of unusual phenomena can be obtained. Almost all cases of unusual phenomena ever reported can be well explained by these combinations.

In process of studies on relation between ship form and her manoeuvrability or on scale effect in manoeuvrability, it becomes necessary to separate the effect of unusual force (which usually improves course stability of ships averagely) from the own course stability of ships. This is because there is qualitative difference in two items. The course stability is governed mainly by principal particulars or rudder area of ships. On the other hand, the unusual force is dependent upon the local ship form such as fullness of upper part of the stern, aperture size over the propeller or the rudder etc., as easily estimated from the stern flow pattern.

It would be a great pleasure of the authors if the present study contributes to the development of studies in this field.

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T. Araki and F. Maruyama graduated from Hiroshima University in 1979 took place in this work as their graduate study.

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