MANOEUVRABILITY

by

Seizo Motora Dr. Eng.

Several works and contributions have been done in Japan in the field of manoeuvrability since last ITTC meeting in Paris at which, decision was made to introduce manoeuvrability of ships as one of the subjects of the ITTC.

In this paper, the author attempts to introduce some of works which the Author thinks are related to the recommendations given by the conference to the Manoeuvrability Committee for its work.

(a) Choice and definition of quantities and qualities to define the manoeuvrability of ships

(1) A simplified analysis of ship motion under steering and proposed steering quality indices.

NOMOTO's method of analysis of Zig-Zag tests to obtain steering quality indices which is introduced by the Author at the last meeting at Paris has been further developed by NOMOTO and more data both for full scale ships and for models have been collected by him.

Detailed explanations about developement of this method with theoretical background are given in Appendix 1 (page A-1 through A-10) of this paper.

(2) A proposal of research of manoeuvrability at low speed or at unsteady condition of motion.

Recently a large tanker and a small tanker full of gasoline collided into each other in a water way in Tokyo Harbour, and the small tanker burst into a huge flame and all the crew on board the ship were killed. They were navigating at slow speed at that time. As shown in this example, most case of collisions will happen to occur in narrow harbours or in water ways where ships will necessarily be slowed down.

In this respect, a proposal is made by YAMANOUCHI as shown in Appendix 2 (page A-11 through A-12) in which he insists upon the necessity of conducting research works on manoeuvrability at low speed or at unsteady condition such as a ship drifting forward with propeller dragged or reversed.

(b) Review of experimental method

A forced yawing technique to obtain the stability derivatives as functions of the frequency has been developed by MOTORA since 1960. A yawing oscillator was built at the University of Michigan and the derivatives for a Great Lakes ore carrier were measured. More improved facilities by which a model can be forced to yaw as well as sway in an arbitrary combination of phase and amplitude is under construction at the University of Tokyo. Detailed explanations are given in Appendix 3 (page A-13 through A-24).

(c) Correlation between model test and ship trial data

Correlation tests between 4.5m model and 12,000GT ship and 5.2m model and 130,000GT ship have been conducted by NOMOTO, and it was found that evident scale effect showed up at small rudder angles both in spiral and Zig-Zag tests as shown in Fig. 1, Fig. 2 and Fig.3 of Appendix 4. At large rudder angle over 20 degrees, scale effect seems to decrease.

According to NOMOTO's opinion, the main cause of difference between model data and ship data at small rudder angle lies on the difference of relative frictional resistance for models and ships which may cause fairly large differnces in propeller loading and in rudder effectiveness.

Detailed explanations are given in Appendix 4 (page A-25 through A-31),

APPENDIX 1

A SIMPLIFIED ANALYSIS ON SHIP MOTION UNDER MANOEUVRE AND PROPOSED STEERING QUALITY INDICES.

by Kensaku Nomoto. Dr. Eng.

What measure of ship manoeuvrability should be reasonable has been an important problem, as mentioned in the decisions and recommendations at the 9th I.T.T.C. The present paper relates to a proposed measure of manoeuvrability based upon a simplified analysis on ship motion under manoeuvre.

This measure, which consists of two indices, relates more to course-keeping and response to steering with moderate helm rather than hard-over turn. The indices for a ship can be determined by analysing proper type of manoeuvre (e.g. Kempf's zig-zag test).

The analysis along this line were carried out for about a hundred actual ships and free-running models and it is found that the indices are good measure of manoeuvrability for those cases.

These indices are not merely a relative measure but represent a dynamic character of a ship under manoeuvre quantitatively, so we can predict ship motion for a given steering within a practical accuracy, using them together with a simple differential equation. The indices can be related theoretically to hydrodynamic derivatives which have been widely used in the analytical treatment, as well as to the empirical measures for manoeuvrability like as turning radius, reach and overswinging angle.

REDUCTION OF THE PRESENT ANALYSIS: The present analysis is based upon the usual linear analysis on the ship motion, using the following form of simultaneous equations of motion,

$$\left.\begin{aligned} \left(\frac{L}{V}\right) m'_y \frac{d\beta}{dt} + Y'_\beta \cdot \beta - \left(\frac{L}{V}\right)\left(m'_x - Y'_\Omega\right)\dot{\psi} &= Y'_\delta \cdot \delta \\ \left(\frac{L}{V}\right)^2 I'_z \frac{d\dot{\psi}}{dt} + \left(\frac{L}{V}\right) N'_\Omega \cdot \dot{\psi} - N'_\beta \cdot \beta &= N'_\delta \cdot \delta \end{aligned}\right\} \qquad (1)$$

where β : drift angle, $\dot{\psi}$: turning angular velocity,

δ : helm angle, V : ship speed, L : ship length,

m'_x, m'_y & I'_z : nondimensional virtual mass and moment of inertia

and Y'_s & N'_s : hydrodynamic derivatives.

We can derive the transfer function from the equations, which describes in this case the response character of a ship to steering, as follows,

$$Y(p) = \frac{\text{Laplace transform of } \dot{\psi}}{\text{Laplace transform of } \delta} = \frac{K(1+T_3 p)}{(1+T_1 p)(1+T_2 p)}$$

where p : parameter of the trasform, which represents a frequency of rudder movement.

K, T_1, T_2 and T_3 are constants composed of the coefficients of Eq. (1).

The transfer function may be simulated by the following simnler form if the frequencies of rudder movement are adequately low (small p), that is

$$Y(p) = \frac{K}{1+Tp},$$

where $T = T_1 + T_2 - T_3$.

Retransforming the above approximate transfer function into the form of equation of motion, we obtain

$$T\frac{d\dot{\psi}}{dt} + \dot{\psi} = K\delta \tag{2}$$

Since the actual movement of a rudder is not hasty and a ship is the less sensitive to the higher frequency steering, this approximation may be valid for the ship motion under the usual manoeuvre.

Fig. 1 - 4 show how we can interprete zig-zag test results for various cases along this line; the chain lines indicate computed ship motions by using Eq.(2) with the proper values of K and T, while the full lines the observed motion. The procedure of defining the values of K and T will be discussed later.

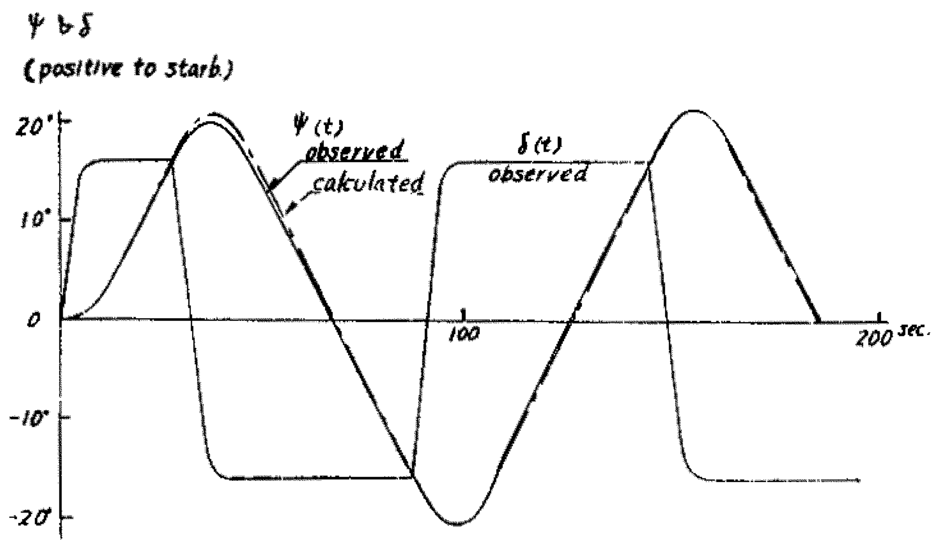


FIG. 1 ZIG-ZAG TEST RESULT FOR A BALLASTED CARGO-BOAT.

There is a sufficient amount of this kind of the test results, so that it may be concluded that the actual motion of a ship may be described roughly by Eq.(2), with the indices K and T which are inherent in each individual ship.

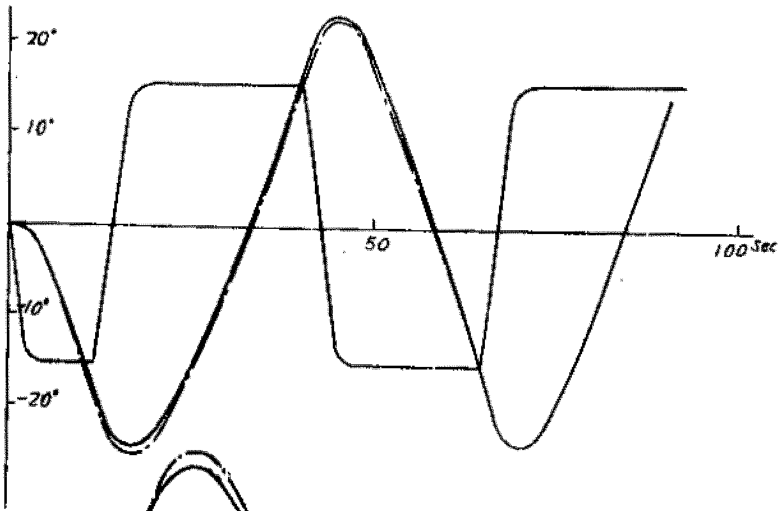


FIG.2 ZIG-ZAG TEST RESULT FOR A WHALE CATCHER.

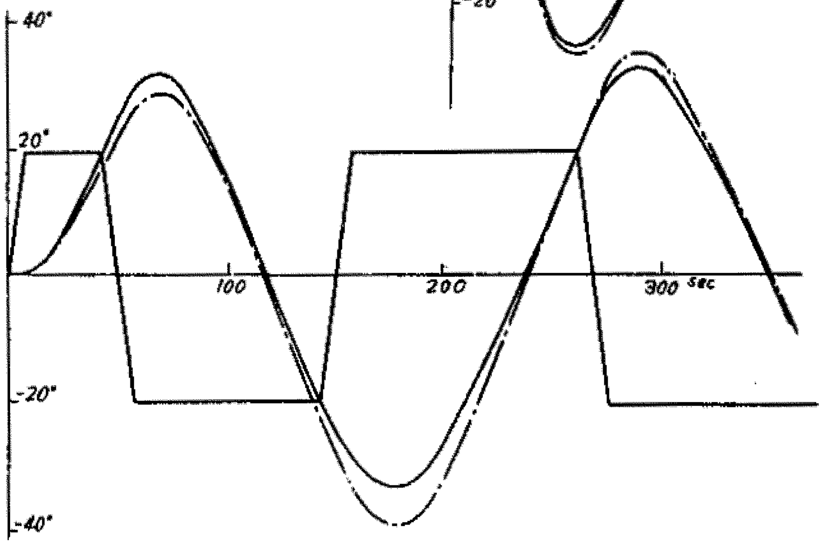


FIG.3 ZIG-ZAG TEST RESULT FOR A FULL-LOADED TANKER.

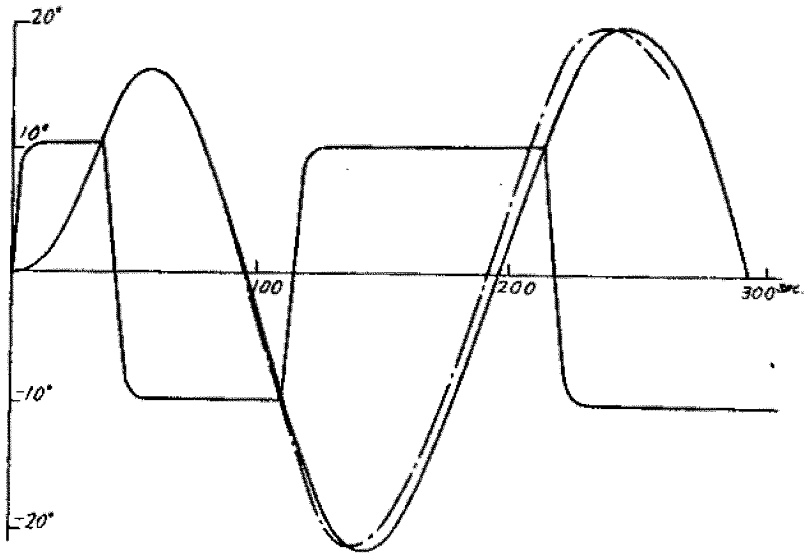


FIG.4 ZIG-ZAG TEST RESULT FOR A FULL-LOADED CARGO-BOAT.

THE STEERING QUALITY INDICES K AND T: Now let us consider the case that the rudder be put over by a certain angle δ_0 when a ship is running straight. We can define motion of a ship from Eq. (2) as

$$\dot{\psi} = K\delta_0(1-e^{-t/T})$$

The angular velocity $\dot{\psi}$ increases exponentially with a quickness depending upon T value and finally settles in a steady value $K\delta_0$ (Fig.5).

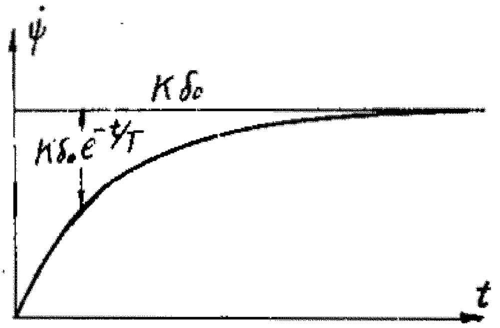


FIG.5 BUILD-UP OF TURNING

The larger K provides the rapider terminal turning and the smaller T the quicker response.

So K may be called as the index of turning ability and T the index of quickness in responding to steering.

It should be noted here that how rapid turning a ship can make terminally and how early she can approach to the terminal motion are quite different things from each other. (In the words of control engineering, the former should be called as static gain and the latter time constant.)

Now let us consider the case that a ship be stimulated to have a certain angular velocity $\dot{\psi}_0$, keeping her rudder amidship throughout. We obtain ship motion in this case as,

$$\dot{\psi} = \dot{\psi}_0 e^{-t/T}$$

The angular velocity $\dot{\psi}$ decays exponentially with a quickness depending upon T value; the smaller T provides the quicker decay and so the better stability on course. A negative T represents instability.

Thus it becomes clear that the stability on course and quickness in responding to rudder are two faces of one character of a ship, as it has been recognized empirically.

In conclusion it may be said that K is the index of turning ability and T the index of quickness in responding to rudder and also of stability on course, and that manoeuvrability of a ship may be represented essentially by the two indices.

Obviously from the analytical reduction of K and T as before, these indices may be written in terms of the hydrodynamic derivatives, as follows;

$$K = \left(\frac{V}{L}\right) \frac{N'_\beta Y'_\delta + Y'_\beta N'_\delta}{Y'_\beta N'_\Omega - (m'_x - Y'_\Omega) N'_\beta}$$

$$T = \left(\frac{L}{V}\right) \left\{ \frac{m'_y N'_\Omega + I'_z Y'_\beta}{Y'_\beta N'_\Omega - (m'_x - Y'_\Omega) N'_\beta} - \frac{m'_y N'_\delta}{N'_\beta Y'_\delta + Y'_\beta N'_\delta} \right\}$$

This expression leads us a nondimensional form of the indices, that is

$K' = \left(\frac{L}{V}\right) K$ and $T' = \left(\frac{V}{L}\right) T$.

K' and T' are composed only of the nondimensional coefficients of Eq. (1), and so may be defined if provided these coefficients for a given ship. There is another and more practical way of defining the indices, however. It is to find those values of the indices with which the equation of motion (2) may describe an observed ship motion under a certain manoeuvre. Kempf's zig-zag test may be a suitable one for the purpose.

ANALYSIS OF KEMPF'S ZIG-ZAG TEST (PRACTICAL PROCEDURE OF DEFINING THE INDICES K AND T FOR A SHIP):

Usually a ship does not keep a straight course with her rudder apparently amidship by reason of miscellaneous factors. Considering the fact we put the angle of helm to be used for the analysis as

$$\delta(t) = \delta_m(t) + \delta_r ,$$

where δ_m : observed angle of helm

δ_r : neutral helm correction that is an unknown constant at the beginning of the analysis.

Putting it into Eq. (2) and integrating the both sides from t = 0 to t = t, we obtain

$$T(\dot\psi - \dot\psi_0) + \psi = K\int_0^t \delta_m(t)\,dt + K\delta_r t \qquad (3)$$

where $\dot\psi_0$: a possible initial angular rate at the start of a test.

Defining a number of sampling time on a zig-zag test record usually at regular intervals, we measure ψ , $\dot\psi$, δ_m and then obtain $\int_0^t \delta_m\,dt$ by numerical integration. A number of equations of the type of Eq.(3) are then made for each sampling time and unknown quantities in these equations are T, K and δ_r. Employing the principle of the least squares, we can solve these equations simultaneously to obtain K and T.

To use an electronic digital computer is practical for the calculations, while it is not so hard to carry on it with convensional hand calculator.

The indices thus obtained may be considered those which describe a ship motion under a zig-zag test most closely on the whole. A check calculation may be carried on, if desired, by putting the obtained indices and observed δ into Eq.(2) and integrating it. Fig. 1-4 illustrate the $\psi(t)$ thus obtained comparing with the observed $\psi(t)$.

APPLICATION OF THE PRESENT APPROACH ON NON-LINEAR MOTION UNDER MANOEUVRE:

Applying the linear analysis to small perturbations about steady turning, we can define K' in turning motion. This K' becomes the ratio of incremental turning curvature to incremental angle of helm in a steady turn and is represented by the slope of the $L/R_s - \delta_o$ curve. This diagram is drawn by plotting the steady turning curvature L/R_s obtained from the spiral test of Dieudonné against angle of helm employed δ_o, like as Fig. 6.

The K' is a function of turning curvature L/R_s by reason of the non-linear changes of the hydrodynamic forces acting upon a ship's hull.

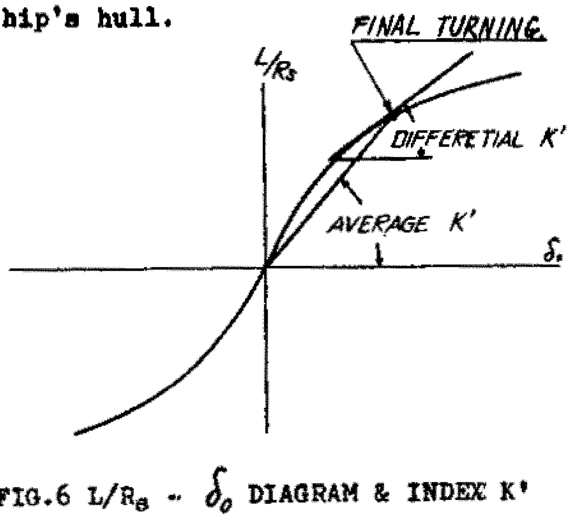


FIG.6 $L/R_s - \delta_o$ DIAGRAM & INDEX K'

Now considering the initial stage of turning, this K' varies gradually with increase of turning curvature, and the ratio of final turning curvature to the applied angle of helm represents some average value of the transient K'. This average K' is also indicated in the figure.

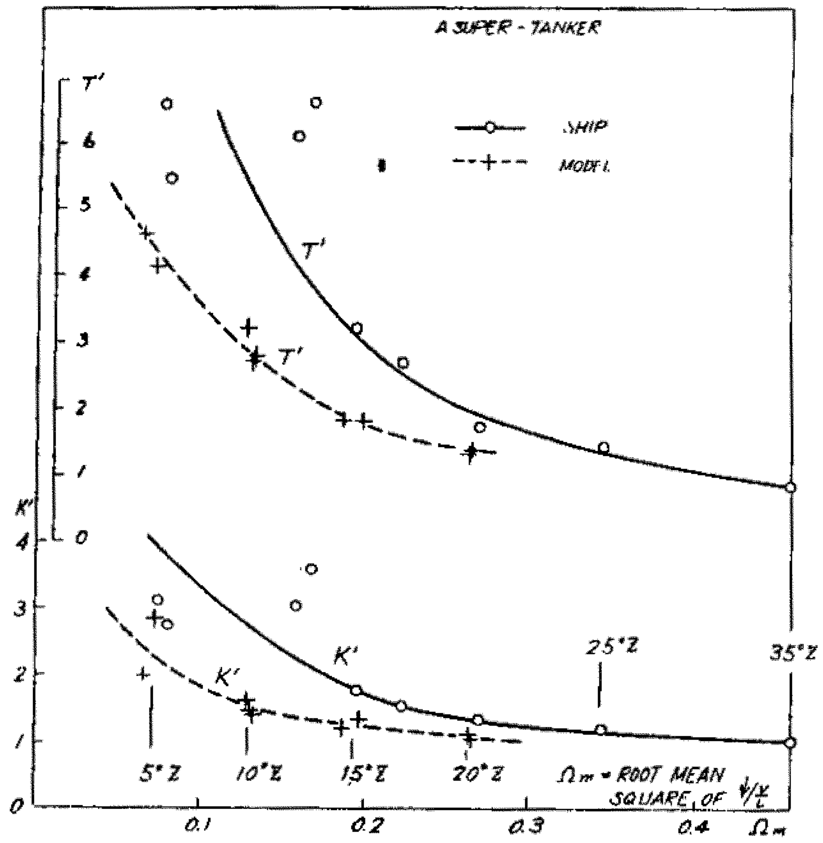


FIG.7 ZIG-ZAG TEST RESULTS FOR A SUPER-TANKER & HER MODEL(1).

In case of turning with a large helm angle, the variation of K' may increase considerably, so that no linear treatment can be adopted in a strict sense. It may be reasonable, however, to construct a linear expression simulating the non-linear phenomenon on the average; the average K' would then be used for the purpose.

Linear analysis on zig-zag manoeuvres should also be based upon this concept. In most cases it is possible to represent closely the actual ship motion observed in the trials with the linear analysis as mentioned before. The indices derived from the trials with different angles of helm employed, however, show sometimes a considerable difference from each other. This suggests that ship motion in the trials is not essentially linear, but is "linear on the average" if linear indices are properly adjusted depending upon the average intensity of motion (rather than upon the helm angle, because a rudder force is usually linear up to a large angle of helm).

Fig. 7 illustrates the indices of a super-tanker and her model against the average turning angular rate in a nondimensional form.

In this case the indices vary very hardly with the average intensity of motion (considerable non-linear effect) by reason of poor stability on course of the super-tanker. Even in this case each individual zig-zag manoeuvre can be not so poorly interpreted using properly adjusted indices.

According to a number of experiments, the more intense is ship motion, the smaller are the indices, assuring that a ship becomes more stable on course when turning, as it has been commonly recognized. It agrees with the K'- L/R_s relation derived from the spiral test as before. This tendency appears the more remarkably for the less course-stable ships.

In conclusion it may be said that K-T representation of manoeuvrability can be adopted even for the non-linear range by introducing the concept of "linear on the average". Considering a wide utility of linear treatment, it is more convenient than an exact non-linear analysis, especially for practical purposes. In this connection, to conduct the zig-zag trials applying several angles of helm and to define the indices as functions of the average intensity of motion may be recommendable.

USUAL MEASURES OF MANOEUVRABILITY AND THE PRESENT INDICES:

The steady turning radious R_s has an immediate relation with the index K' as before, that is,

$$L/R_s = K'\delta_0 ,$$

where the average K' should be used.

The "turning lag" and "reach", which has been used as a measure for quickness in responding to steering, may be written in terms of T as follows,

$$\text{turning lag} = T + t_1/2$$

$$\text{reach} \doteqdot V(T + t_1/2) = T'L + Vt_1/2$$

where t_1 : time spent to set a helm (fairly smaller than T except smaller crafts)

V : ship speed.

The overswinging angle has been widely used as a measure of controllability obtained from the zig-zag trials. This angle is usually measured from helm reversing to extreme course deviation, but it is affected by a speed of a steering gear, which is not a ship's charactor; the slower is the speed, the larger is the over-swinging. So modifying the definition of the angle so as to be measured from the time when a rudder passes amidship (Fig.8), we can find the following relation through integrating Eq. (2) for a zig-zag manoeuvre, that is,

the over swinging angle θ_{OS} is nearly proportional to $K'T'\delta_0$,

where δ_0 : angle of helm employed.

It should be noted that the overswinging angle as a measure of manoeuvrability has a shortcoming that it can not discriminate good turning ability with quick response to rudder (large K and small T) from poor turning ability with slow response (small K and large T); the former yields good manoeuvrability and the latter poor one.

In order to cover this shortcoming, it is recommendable to use another measure of quick response, "course changing lag" T_L, so termed temporarily, together with the overswinging angle. T_L is defined as a time duration from rudder passing amidship to extreme heading deviation, as is shown in Fig.8.

Using the equation of motion (2), we can find that

the course changing lag T_L is nearly proportional to T.

So we obtain the relation that

$\theta_{OS}/T_L'\delta_0$ is nearly proportional to K',

where $T_L' = (V/L)\ T_L$.

$\theta_{OS}/T_L'\delta_0$ and T_L' may be obtained immediately from the zig-zag trial and be used together as a measure of manoeuvrability. These two quantities chagne their values with the average intensity of ship motion as similar as K' and T', as is shown in Fig.9.

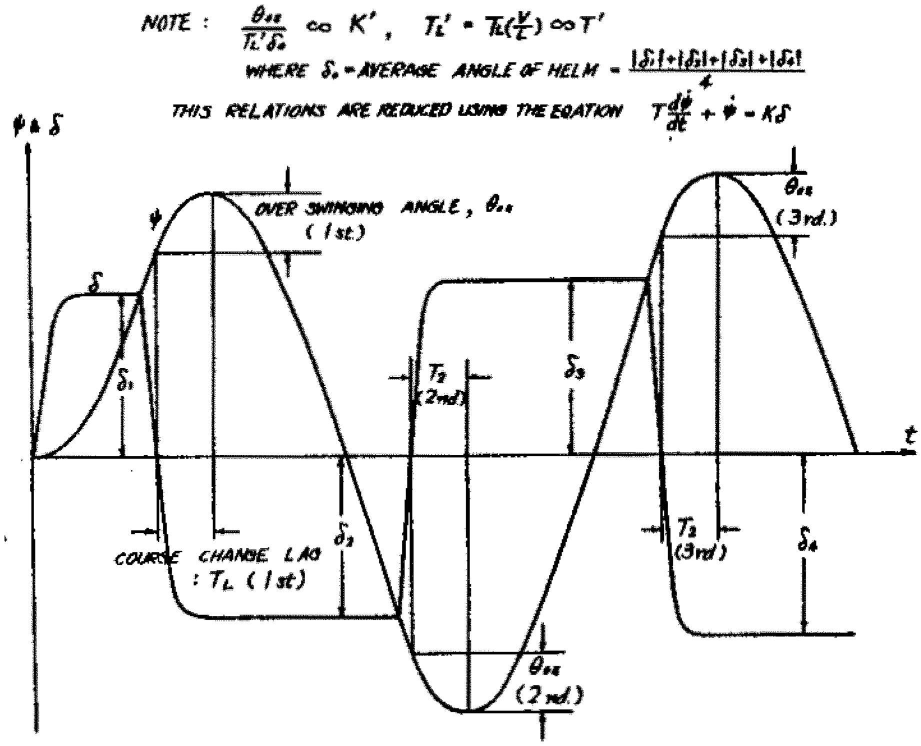


FIG. 8 PRESENT DEFINITION OF OVERSWINGING ANGLE & COURSE CHANGING LAG.

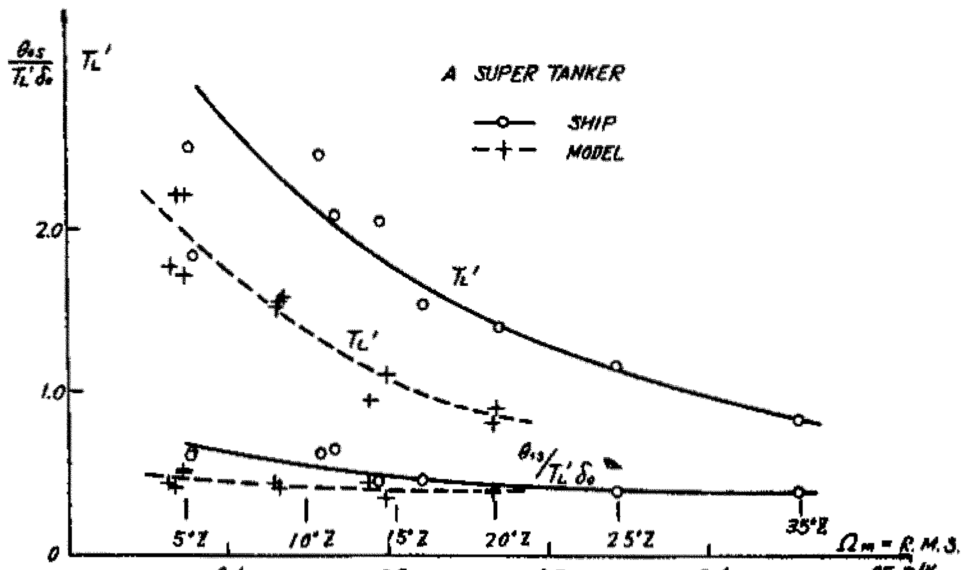


FIG. 9 ZIG-ZAG TEST RESULTS FOR A SUPER-TANKER & HER MODEL (2)

APPENDIX 2

A Proposal of Research on Maneuverability at low speed or at unstationary condition of motion

by Yasufumi Yamanouchi

The maneuverability of the ship is still an undeveloped research field, although the ship has been steered by a simple rudder for centuries with few troubles. We can say that the analytical research of the maneuverability of the modern type of ship has just been taken up. Namely it is very recent that we started to try to express the maneuverability by the form of derivatives, or the coefficients of the differential equations which are supposed to show the motion of the ship, or by some other forms for example by so called K and T indices that are determined by the zig-zag test, and started to try to fix the standards of the maneuverability based on these values.

Accordingly at this stage, these researches are restricted only for the case when the ship is sailing on her service speed, and very few researches have been performed or planned for the case when the ship's motion is unstationary, or the speed is varying or the ship is going astern. However, as a matter of fact, while the ship is sailing ocean, she advances almost on a straight line along the pre-set course, and she is not steered so often except the oscillatory helm angle around the bias determined through the auto pilot system, and in this kind of situation, the maneuverability and steering quality of the ship is not so serious problem, except some considerations on her course keeping qualities.

On the other hand, the maneuverability is an important problem rather in entering or going out of the port, when the ship advances by slow speed or slowing down or changing her speed. At this situation, rather a fine steering is necessary, and because of many chances of encounter to other ships or the shore, the rudder is steered very frequently. The captain orders a large helm or a hard over at her low speed, or orders the stopping or go astern, at the same time.

The choice of maneuvering and the motion of the ship after the helm is the most serious concern for the captain, and also has much to do with the safety of the ship at sea. Actually many accidents like the collisions have been broken out in these situation, because of the mis-choice of the maneuver or the mis-prediction of the motion by the helm, or by the inherent poor maneuverability of that ship.

Recently, in view of the miserable disasters which happened in Japanese port, we have just started to study the following subjects. Because of the importance of the problem, we propose that these should also be pursued in the world wide scale. Namely, putting down from simpler one, they are :

1) The change of the rudder effect after the screw stopped its turning.

2) The difference of the rudder effect while the screw is turning in idle, or fixed.

3) The change of the side force given by the turning screw, by the variation of the depth of immersion. It can happen that the ship tends to swing her stem to starboard in full condition against the captain's expectation, even though she tended to swing to port in her light condition.

4) The behavior of the ship when the screw is turning inverse in spite of the inertia speed ahead, after a sudden stopping was ordered.

5) The behavior of the twin screw ship when one screw is turning ahead and the other is turning astern besides the helmed rudder,

and so on. We expect in many research establishment in the world, these are adopted, and satisfactory informations will be given to the captain about the maneuverability in these kind of case.

APPENDIX 3

Forced Yawing Technique to Obtain the Stability Derivatives as Frequency Dependents.

by SEIZO MOTORA
Dr. of Engineering

1. Introduction

In dealing with the responce of ships under the influence of frequent steering or periodic disturbances, it will be necessary to know if the stability derivatives are the functions of the frequency.

For this purpose, a forced yawing technique has been developed by the author and Prof. R. B. Couch at the University of Michigan [1].

At the end of 1960, the University of Michigan had a project of investigating maneuverability of ships in restricted waters. And it was found that the forced yawing technique was suitable for this project since the rotating arm technique was not available in channels. Therefore, the first arm to have developed the forced yawing technique was to obtain the stability derivatives in restricted waters.

But in the course of time, the author became awere that this technique can be used for the purpose to obtain the stability derivatives as the functions of the frequency.

2. Set-up of the Instrumentation

The forced yawing technique is quite similar to the technique developed at DTMB by Gertler and Goodman[2] to obtain the stability derivatives for depth control of submarines. In the forced yawing test, a model is forced to yaw about its center of gravity and also forced to sway. The combination of amplitude and phase of yaw and sway will be such that:

a) pure sway; a model sways without yaw

b) pure yaw; a model yaws without drift. ie., the velocity of the model is always tangential to the locus of its C. G.

To conduct these experiments, it is necessary to build an oscillator which is capable of making a model to yaw and sway with arbitrary combination of the amplitude and phase. In the case of an oscillator built at the University of Michigan, sway motion was eliminated mainly by financial reason.

A schematic of the set-up of the oscillator and the dynamometer is shown in Fig. 1. As seen in Fig. 1, a vertical shaft Ⓕ is attached to the towing carriage and is oscillated by a driving motor Ⓐ through an arm Ⓓ and a connecting rod Ⓒ. The amplitude of yaw is adjusted by the eccentricity at the disc Ⓑ. To the shaft Ⓕ, an arm Ⓖ is fixed and two thin aluminium pipes Ⓗ and Ⓘ are attached to the arm through slide bearings so that the model is allowed to heave and trim. Pipes Ⓗ and Ⓘ are fixed to the model through pivots Ⓛ and Ⓜ to allow the model to roll and pitch. To the rods Ⓗ and Ⓘ, three sets of wire strain gauges are attached from which the axial force, the side force and the yawing moment applied to the model can be measured.

The amplitude of yaw is adjustable from zero to ten degrees and the frequency of yaw is adjustable from zero to one per second, and the maximum angular velocity attained is comparable to that of the full scale ship turning with 40 degrees rudder angle. The forces and moment picked up by the wire strain gauges are recorded by a Sanborn recorder together with the motion of the model and time signals. Owing to practical reasons, two side forces Y_2 and Y_1, one at the C. G of the model and one at 1.25ft forward of the C. G are measured instead of measuring the side force and the yawing moment.

An example of record obtaind on S. S Benjamin Fairless is shown in Fig. 3.

An improved type of the oscillator which is capable of giving forced sway as well as forced yaw to a model is now being constructed at the

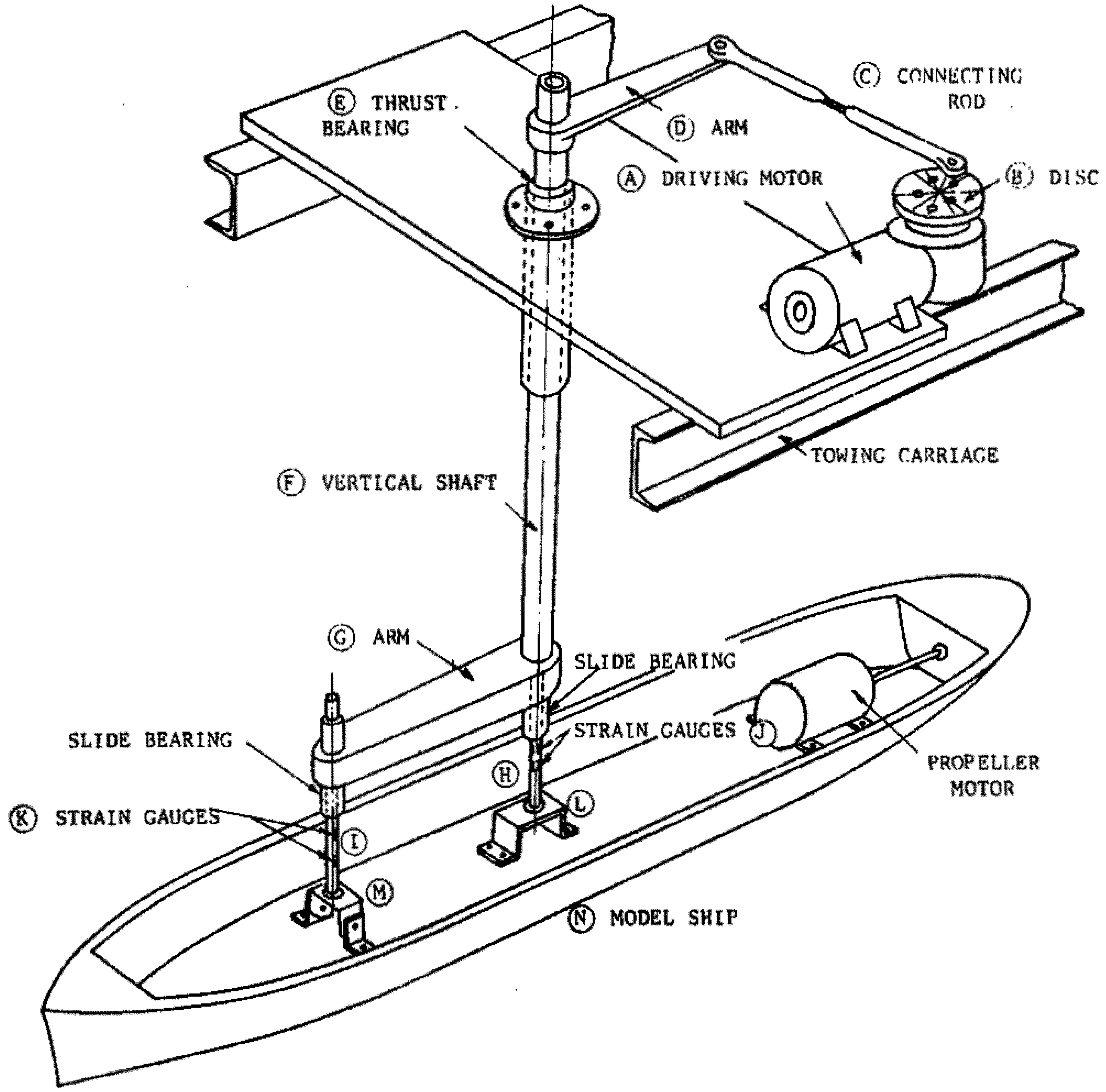


FIG. 1 SET-UP OF SHIP MODEL OSCILLATOR AND DYNAMOMETER INSTALLED AT THE UNIVERSITY OF MICHIGAN

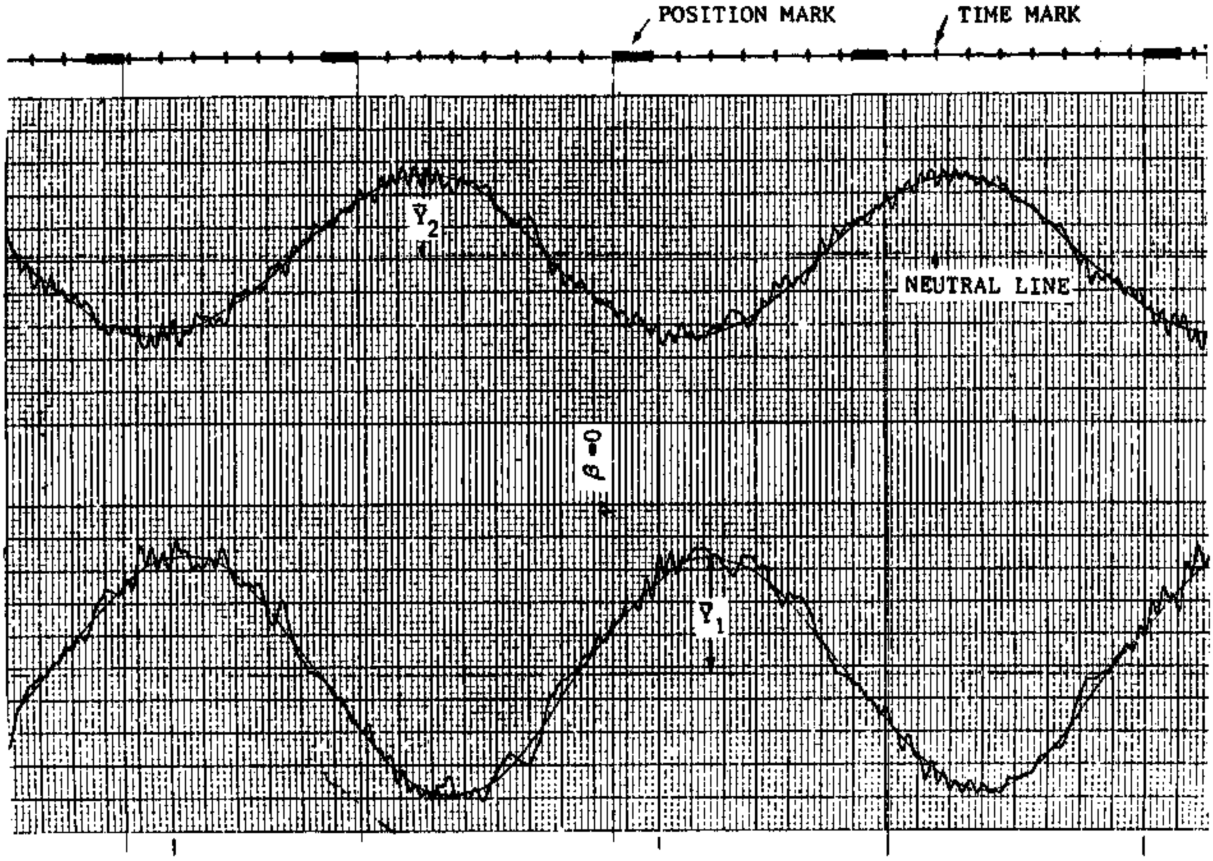


FIG. 3 AN EXAMPLE OF THE RECORD

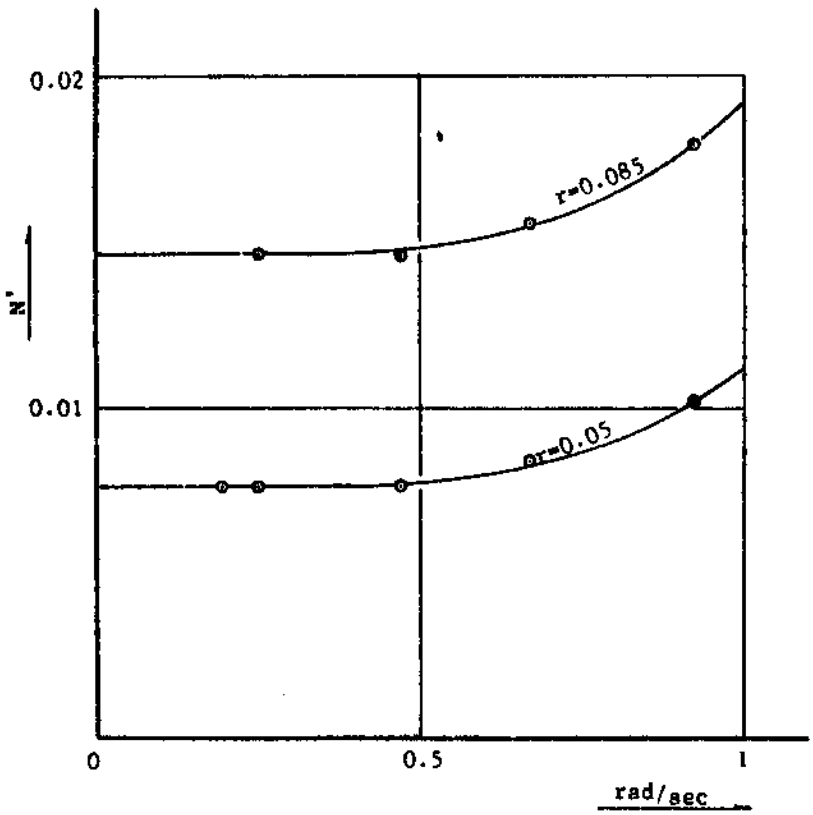


FIG. 5 EFFECT OF FREQUENCY ON YAWING MOMENT COEFF.

University of Tokyo. Fig. 2 shows the schematic of the set-up of the oscillator. The bed of the yawing oscillator similar to the one built at the University of Michigan is mounted on rails (K) fixed to the towing carriage so that whole set-up of the yawing oscillator can be forced to sway by an eccentric disc (F) and a connecting rod (G). The amplitude of the sway can be adjusted by the eccentricity of the disc (F), and the phase between sway and yaw can be adjusted by a phase adjuster (H).

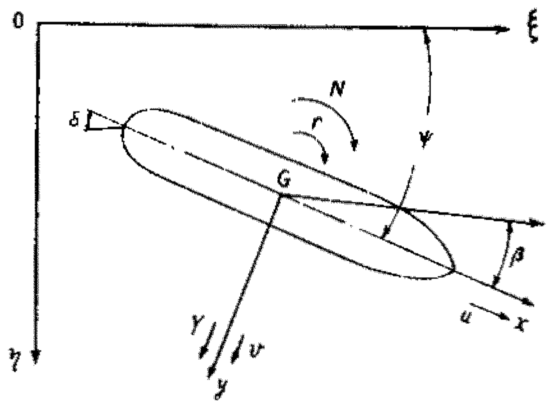
The side forces at two points and the axial force are measured by three sets of wire strain gauges attached to three beams (L) (M) and (N) which are connected to the model by pivoted arms (O) (P) and (Q). The model will be self propelled so that the reading of the axial force dynamometer is almost zero.

3. Method of Analysis.

3.1 Equation of motion.

Equation of motion of a solid moving in an ideal fluid is written as follows:

$$\left.\begin{aligned} (m + m_y)\dot{v} + m_y \alpha \dot{r} &= -(m + m_x) u r + Y \\ (I_z + J_z)\dot{r} + m_y \alpha \dot{v} &= (m_x - m_y) u v + N \end{aligned}\right\} \qquad \cdots\cdots (1)$$



Meaning of each symbol is shown in the list of symbols attached to the end of the appendix. Developing Y and N into linear functions of $\dot{v}$ and $\dot{r}$, and letting $(m_x - m_y)uv$ term to be included in $N_v \cdot v$ term, we get:

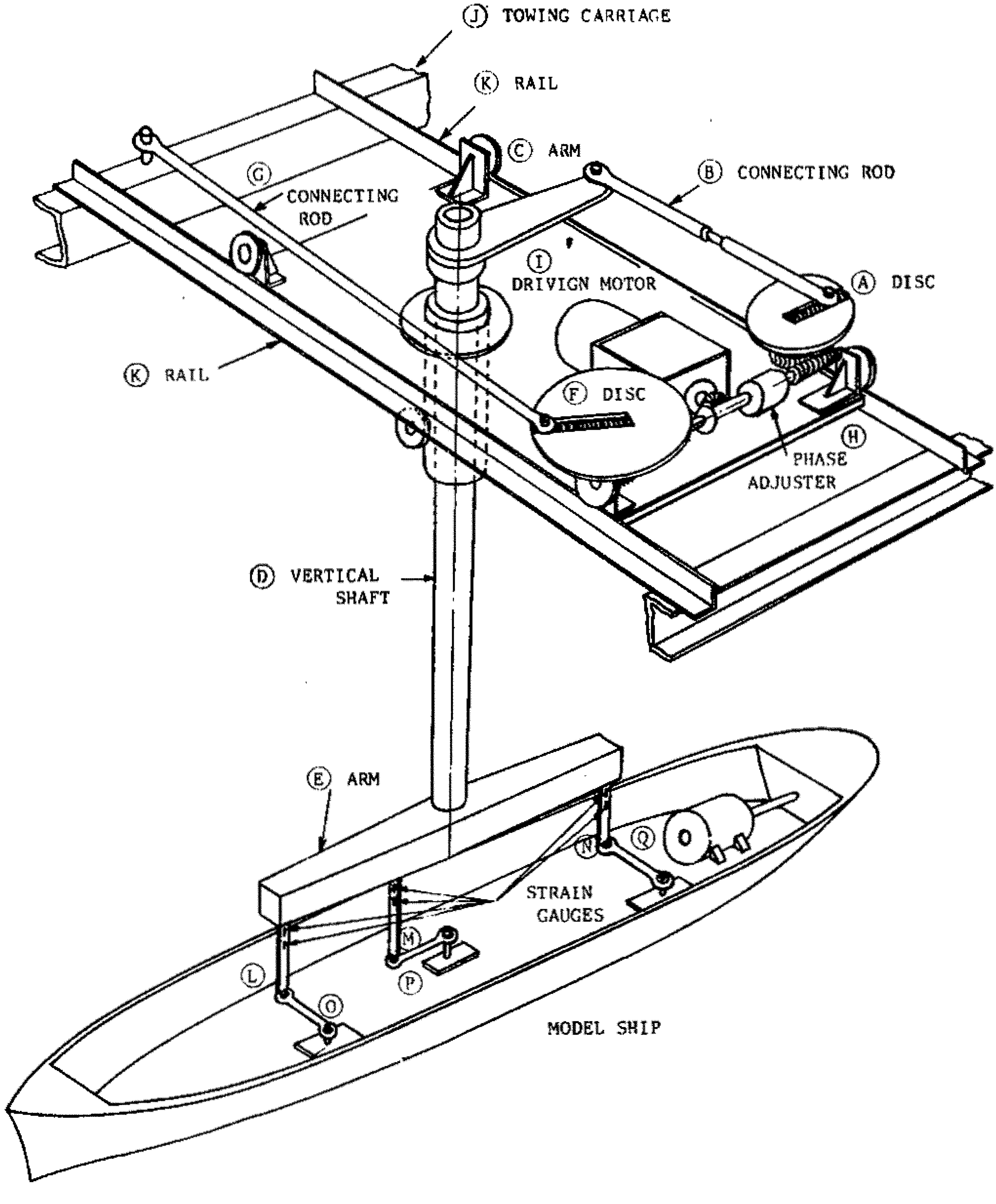


FIG. 2 SET-UP OF SHIP MODEL OSCILLATOR AND DYNAMOMETER TO BE INSTALLED AT THE UNIVERSITY OF TOKYO

$$\left.\begin{aligned}(m+m_y)\dot{v}+m_y\alpha\dot{r}&=\{-(m+m_x)u+Y_r\}r+Y_v\cdot v+Y_0\\(I_z+J_z)\dot{r}+m_y\alpha\dot{v}&=N_r\ r+N_v\cdot v+N_0\end{aligned}\right\}\cdots\cdots\cdots(2)$$

where Y_0 and N_0 are the side force and the moment applied to the model by the oscillator.

For small angle of yaw, we can put

$$v \doteqdot -U\beta, \qquad u \doteqdot U$$

therefore, we get:

$$\left.\begin{aligned}-(m+m_y)U\dot{\beta}+m_y\alpha\dot{r}&=\{-(m+m_x)U+Y_r\}r+Y_\beta\cdot\beta+Y_0\\(I_z+J_z)\dot{r}-m_y\alpha U\dot{\beta}&=N_r\cdot r+N_\beta\cdot\beta+N_0\end{aligned}\right\}\cdots\cdots(3)$$

3.2 When sway motion is neglected.

First, a model is towed with specified drift angle β, and the side force and moment are measured.

$$\left.\begin{aligned}Y_0&=Y_\beta\cdot\beta\\N_0&=N_\beta\cdot\beta\end{aligned}\right\}\cdots\cdots\cdots\cdots\cdots\cdots(4)$$

Thus we get Y_β and N_β.

Then the model is forced to yaw with specified amplitude and period. The locus of the C. G. of the model is restrained on a staight course. Therefore,in this particular case,

$$\psi=\beta, \qquad \dot{\beta}=r \quad\cdots\cdots\cdots\cdots\cdots\cdots(5)$$

putting (5) into (3), we get:

$$\left.\begin{aligned}Y_0&=-(m+m_y)Ur+m_y\alpha\dot{r}-\{-(m+m_x)U+Y_r\}r-Y_\beta\cdot\beta\\N_0&=(I_z+J_z)\dot{r}-m_y\alpha Ur-N_r\cdot r-N_\beta\cdot\beta\end{aligned}\right\}\cdots\cdots(6)$$

Y_0 and N_0 are measured by the dynamometer and are expressed in the following form where ε_1 and ε_2 are the phase lag of side force and moment behind the yawing motion.

$$\left.\begin{aligned}Y_0&=\overline{Y}_0\cos(\omega t-\varepsilon_1)\\N_0&=\overline{N}_0\cos(\omega t-\varepsilon_2)\end{aligned}\right\}\cdots\cdots\cdots\cdots\cdots\cdots(7)$$

Since β is sinusoidal,

$$\left.\begin{aligned} \beta &= \bar{\beta}\cos\omega t \\ r &= \dot{\beta} = -\bar{\beta}\,\omega\sin\omega t \\ \dot{r} &= \ddot{\beta} = -\omega^2\beta \end{aligned}\right\} \cdots\cdots (8)$$

Putting (7) and (8) into (6) we get:

$$\left.\begin{aligned} \frac{\bar{Y}_1\cos\varepsilon_1}{\bar{\beta}} &= -m_y\,\omega^2\alpha - Y_\beta \\ \frac{\bar{Y}_1\sin\varepsilon_1}{\bar{\beta}\,\omega} &= (m_y - m_x)U + Y_r \\ \frac{\bar{N}_1\cos\varepsilon_2}{\bar{\beta}} &= -(I_z + J_z)\,\omega^2 - N_\beta \\ \frac{\bar{N}_1\sin\varepsilon_2}{\bar{\beta}\,\omega} &= m_y\,\alpha\,U + N_r \end{aligned}\right\} \cdots\cdots (9)$$

Therefore we can obtain Y_r and N_r and J_z provided m_y and α are known.

In this case, Y_β and N_β are obtained from statical test. Therefore, they cannot be obtained as frequency dependents.

Therefore, this method is not suitable to obtain stability derivatives as frequency dependents.

3.3 When sway motion is added.

a) Pure sway.

The model is forced to sway while the angular velocity is kept to be zero.

Thus:

$$\left.\begin{aligned} Y_0 &= \bar{Y}_0\cos(\omega t - \varepsilon_1) = -(m + m_y)U\dot{\beta} - Y_\beta\cdot\beta \\ N_0 &= N_0\sin(\omega t - \varepsilon_2) = -m_y\,\alpha\,U\dot{\beta} - N_\beta\cdot\beta \end{aligned}\right\} \cdots\cdots (10)$$

Since β is sinusoidal, we get:

$$\left.\begin{aligned}
\frac{\bar{Y}_0 \cos \varepsilon_1}{\bar{\beta}} &= -Y_\beta \\
\frac{\bar{Y}_0 \sin \varepsilon_1}{\bar{\beta}\,\omega} &= (m + m_y)\,U \\
\frac{\bar{N}_0 \cos \varepsilon_2}{\bar{\beta}} &= -N_\beta \\
\frac{\bar{N}_0 \sin \varepsilon_2}{\bar{\beta}\,\omega} &= m_y \alpha\, U
\end{aligned}\right\} \cdots\cdots (11)$$

From (11) we can get Y_β, N_β, m_y and α.

b) Pure yaw.

The model is forced to yaw so that drift angle β is always kept to be zero ie., without sway.

Therefore, puting $\beta = 0$, $\dot{\beta} = 0$ in eq. (3), we get:

$$\left.\begin{aligned}
Y_0 &= m_y \alpha\, \dot{r} - \{-(m + m_x)\,U + Y_r\}\, r \\
N_0 &= (I_z + J_z)\,\dot{r} - N_r \cdot r
\end{aligned}\right\} \cdots\cdots (12)$$

Since $r = \bar{r} \cos \omega t$, $\dot{r} = -\bar{r}\omega \sin \omega t$, we get:

$$\left.\begin{aligned}
\frac{\bar{Y}_0 \cos \varepsilon_1}{\bar{r}} &= (m + m_x)\,U - Y_r \\
\frac{\bar{Y}_0 \sin \varepsilon_1}{\bar{r}\,\omega} &= -m_y \alpha \\
\frac{\bar{N}_0 \cos \varepsilon_2}{\bar{r}} &= -N_r \\
\frac{\bar{N}_0 \sin \varepsilon_2}{\bar{r}\,\omega} &= -(I_z + J_z)
\end{aligned}\right\} \cdots\cdots (13)$$

From (13), we can obtain Y_r, N_r, J_z and $m_y \alpha$.

4. Examples of data obtained.

Examples of data obtained at the University of Michigan are shown in Fig. 3 through Fig. 6. Fig. 3 is the example of oscillogram of a yawing test. Side forces at two points are measured instead of measuring the side force and the moment.

From these record, stability derivatives are obtained as shown in Fig. 4 and Fig. 5. For the values of added mass m'_y and added moment of inertia J_z, data from [3] are employed.

As was stated in 1, this experiment was conducted to investigate the maneuverability of ships in restricted waters. And stability derivatives needed were ones for very low frequency.

Therefore, experiments were conducted with several combinations of amplitude and fregqency so that stability derivatives for different frequencies were obtained. Fig. 6 shows an example for moment coefficient. From Fig. 6, it will be noticed that for lower frequency than $0.5^{rad}/sec$, the derivative is practically constant. Thus, this constant value was used as the derivative for motion of very low frequency.

It will be also noticed that the effect of frequency upon the derivatives is appreciable at high frequency. But as was stated in 2, it is not suitable to discuss about the effect of frequency on this diagram because the sway motion is eliminated in this experiment.

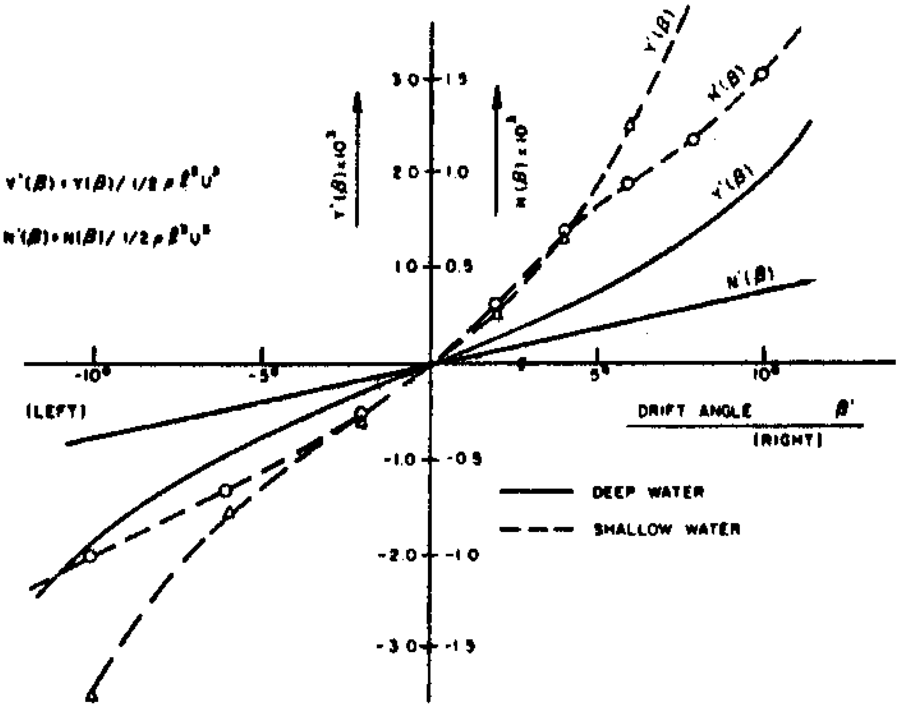


FIG. 4 SIDE FORCE AND YAWING MOMENT COEFFICIENT VERSUS DRIFT ANGLE IN DEEP WATER AND IN SHALLOW WATER

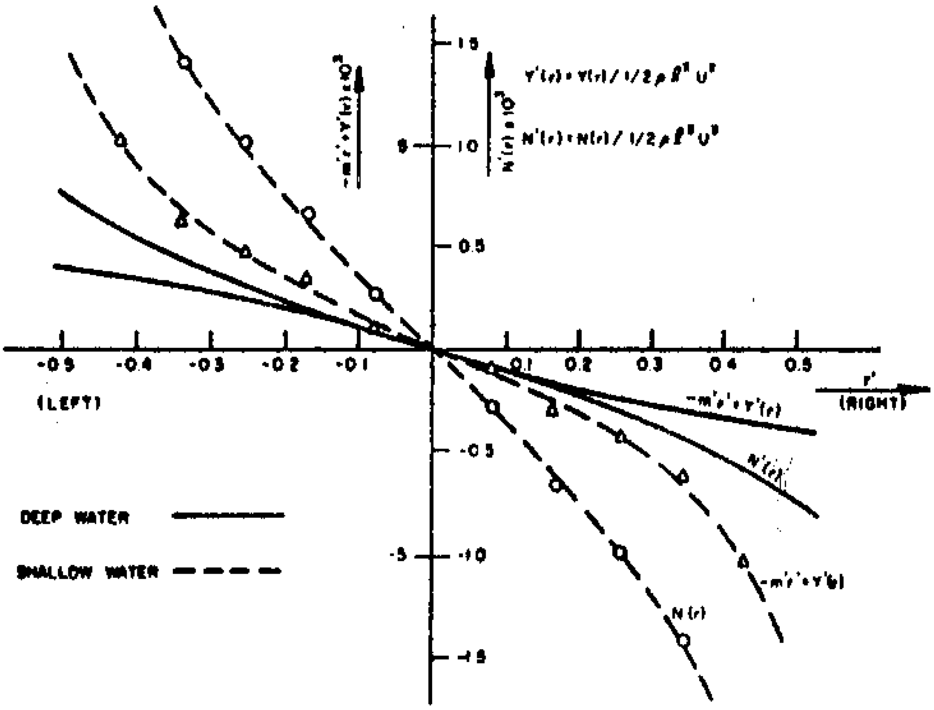


FIG. 5 SIDE FORCE COEFFICIENT AND YAWING MOMENT COEFFICIENT VERSUS ANGULAR VELOCITY IN DEEP WATER AND SHALLOW WATER

LIST OF SYMBOLS

G or C.G. Center of gravity

I_z Moment of inertia about z axis

J_z Added moment of inertia about z axis

L, ℓ Length of the ship

m Mass

m_x Longitudinal added mass

m_y Transverse added mass

N Moment about z axis

N' $N/\frac{1}{2}\rho\ell^3U^2$

$N_{\dot{v}}$ $\partial N/\partial\dot{v}$

N_r $\partial N/\partial r$

N_β $\partial N/\partial\beta$

N'_r $N_r/\frac{1}{2}\rho\ell^4U$

N'_β $N_\beta/\frac{1}{2}\rho\ell^3U^2$

O Origin of co-ordinate

$r=\dot{\psi}$ Angular velocity about z axis

U Ship speed

u x component of velocity

v y component of velocity

x x co-ordinate

Y Side force

Y_v, Y_r Derivatives

Y' $Y/\frac{1}{2}\rho\ell^2U^2$

Y'_r $Y_r/\frac{1}{2}\rho\ell^3U$

Y'_β $Y_\beta/\frac{1}{2}\rho\ell^2U^2$

y y co-ordinate

d Distance between C.G. and center of longitudinal added mass

β Drift angle

δ Rudder angle

ψ Heading angle

ω Circular frequency of yawing

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3 Motora S. "On the measurements of Added Mass and Added Moment of Inertia of ships in Steering Motion.
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APPENDIX 4

SOME MODEL EXPERIMENTS AND SHIP CORRELATION IN RESPECT TO MANOEUVRABILITY

by Kensaku Nomoto Dr. Eng.

This paper relates to some model experiments and ship correlation in respect to manoeuvrability, carried out at the Osaka University Tank under co-operation of Kawasaki Dockyard Co. and Sasebo Heavy Industries Co. The standard zig-zag tests were carried out for a 13 000 DW cargo liner and her model at various load conditions, while the similar tests as well as turning and spiral tests were done for a 130 000 DW super-tanker and her model at full load condition.

Ship and model particulars are shown in Table I.

TABLE I SHIP & MODEL PARTICULARS

KIND OF SHIP	CARGO LINER SHIP	CARGO LINER MODEL	SUPER - TANKER SHIP	SUPER - TANKER MODEL
L × B × D (m)	150x20.5x12.9	4.500x0.614x -	276x43x22.2	5.222x0.814x -
FULL LOAD				
d	9.3 m		16.5 m	
W	19 330 t		162 400 t	
C_B	0.65		0.81	
MAIN ENG.	DIESEL	SHUNT MOTOR	STEAM TURBIN	SHUNT MOTOR
POWER	11 500 BHP		28 000 SHP	
R.P.M.	118		105	
SEA SPEED	ab. 19 kt		ab. 16.5 kt	
RUDDER	BALANCED RUDDER		BALANCED RUDDER	
A/Ld	1 / 62		1 / 67.6	
ASPECT R.	1.65		1.42	
THICK. R.	0.189		0.158	
PROPELLER	SINGLE		SINGLE	
D	5.600 m	0.159 m	7.400 m	0.140 m
P / D	0.940	0.840	0.730	0.800
E. A. R.	0.470	ab0.45	0.575	0.400
BLADES No.	4	4	5	4

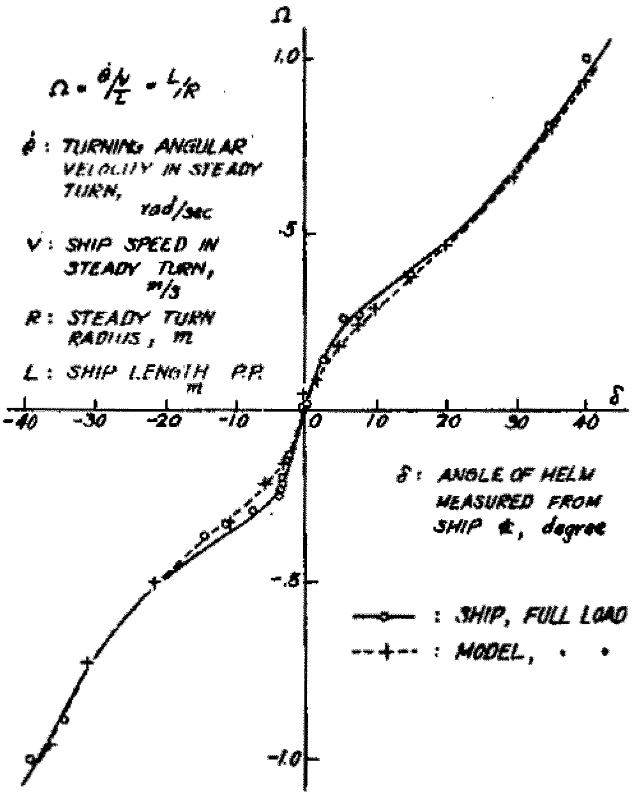

Fig. 1 SPIRAL TEST RESULTS FOR A SUPER-TANKER & HER MODEL

<u>Fig. 1</u> illustrates the spiral test results for the super-tanker and her model in a nondimensional form. According to the results the model-ship correlation seems satisfactory for a hard-over turn, but not for a slight helm. The results show that the ship is less stable on course than predicted from her free-running model when running nearly straight.

This tendency is clearly shown also in <u>Fig.2 and 3</u> which relate to the zig-zag manoeuvre results. The nondimensional indices K' and T' are derived by analysing the zig-zag trial adopting the procedure discussed in Reference (1) but with some refinement using the least squares method (cf. page A-5, Appendix 1). The larger K' indicates the better turning ability (i.e. the smaller turning circle) and the smaller T' the better stability on course and the quicker response to steering. The parameter Ω_m is the nondimensional root mean square value of turning angular velocities during a zig-zag trial and so may be used as a scale of average intensity of the turning motion. According to the results, the ship's T' is much larger than the one of her model for the smaller Ω_m and it means that the ship is less stable on course when running nearly straight and slower in responding to steering than predicted from her model.

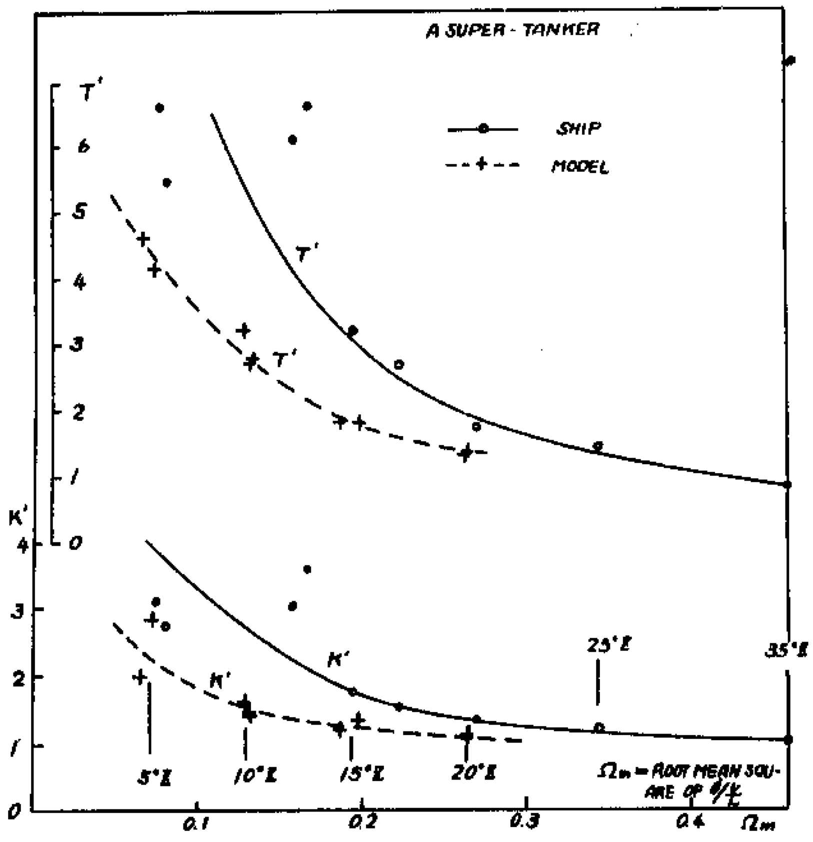

Fig. 2 ZIG-ZAG TEST RESULTS FOR A SUPER-TANKER & HER MODEL (1)

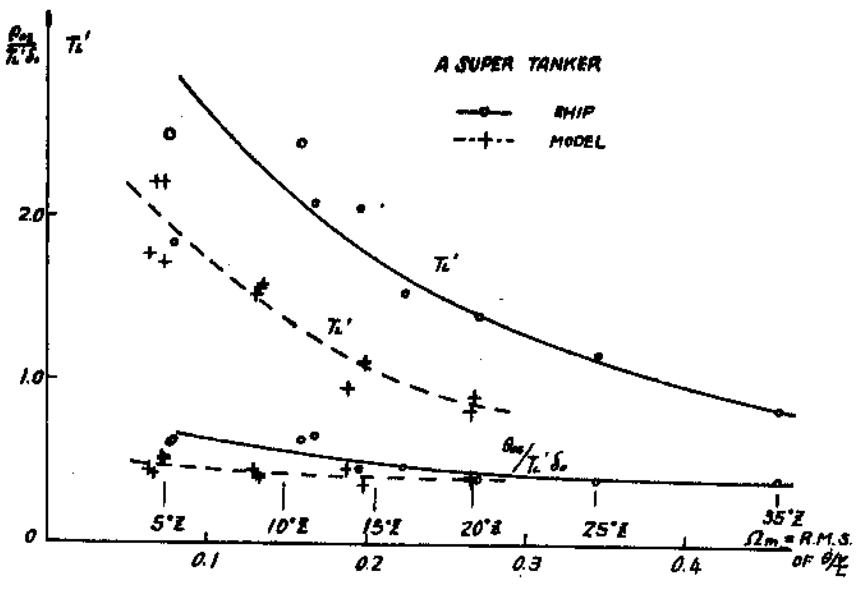

Fig.3 ZIG-ZAG TEST RESULTS FOR A SUPER-TANKER & HER MODEL (2).

Fig. 3 relates to another and more immediate analysis on the zig-zag manoeuvre; to read from a test record the overswinging angle θ_{os} and course changing lag T_L, as defined in Fig. 8 of Appendix 1 (page A-10), and to plot $\theta_{os}/T_L' \delta_0$ and T_L' against Ω_m where $T_L' = (V/L)\ T_L$, V and L denote ship speed and length respectively and Ω_m is the same as in Fig. 2. T_L' is a nondimensional measure of quickness in responding to steering (Appendix 1, page A-9). T_L' of the ship is considerably larger than model's, leading us to the same conclusion as from the spiral test and K-T analysis upon the zig-zag manoeuvres.

Fig.4 is the similar results of the zig-zag manoeuvre for a cargo-liner and her model under roughly full loaded condition and Fig. 5 relates to 10 degree-zig-zag trial results for the liner and her model under various load conditions. These results show that the ship is less stable on course and slower in responding to steering than predicted from model experiments.

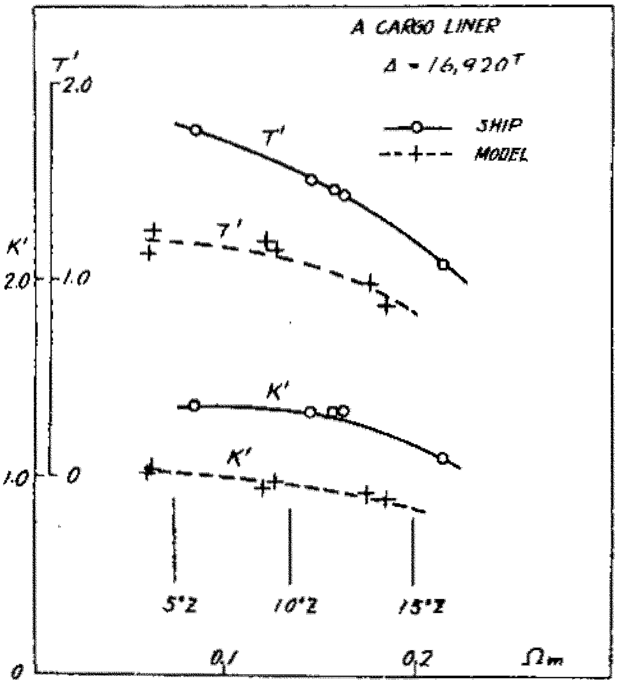

Fig.4 ZIG-ZAG TEST RESULTS FOR A CARGO-LINER & HER MODEL, ROUGHLY FULL LOADED.

In conclusion it may be said that there is a considerable model-ship disagreement upon stability on course, but not upon turning performance at hard-over. This discrepancy may relate to the difference in propeller loadings between a ship and her free-running model, depending upon the larger relative frictional resistance of the latter. The lighter loading of a propeller (that means the weaker slip stream) yields the smaller relative rudder force for the same corresponding speed, so that an actual ship rudder must be less effective than its geometrically simi-

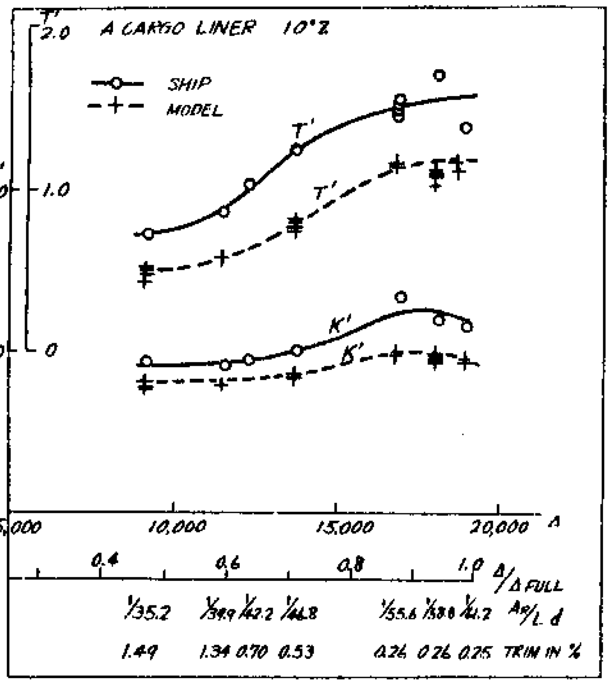

Fig.5 ZIG-ZAG TEST RESULTS FOR A CARGO-LINER & HER MODEL UNDER VARIOUS LOAD CONDITIONS.

lar model, when running nearly straight. The smaller rudder effectiveness is reflected in the worse stability on course.

In regard to hard-over turn, however, additional resistance is so large and frictional resistance becomes relatively so small that the propeller loadings of the two are nearly the same, providing nearly the same rudder effectiveness and then satisfactory model-ship correlation.

Fig.6 relates to some consideration about the model-ship correlation along this line. It illustrates the indices K' and T' derived from the zig-zag manoeuvres, as before, for the super-tanker and her model with alternative rudder sizes against "effective rudder area ratio". This ratio is defined as

A_R / Ld for models and

$(A_R / Ld) \times \dfrac{\text{ship's rudder effectiveness}}{\text{model rudder effectiveness}}$ for ships,

where A_R denotes rudder area.

The rudder effectiveness is a function of propeller loading and it can be estimated by computing propeller slip for a ship and model respectively and then refering to propeller-rudder system open test results (Ref. 2). In the present case the rudder effectiveness of the super-tanker is much less than her model; geometric relative rudder size of 1 / 67.6 for the actual ship corresponds only to 1 / 97.2 for her model on the scale of effective rudder size.

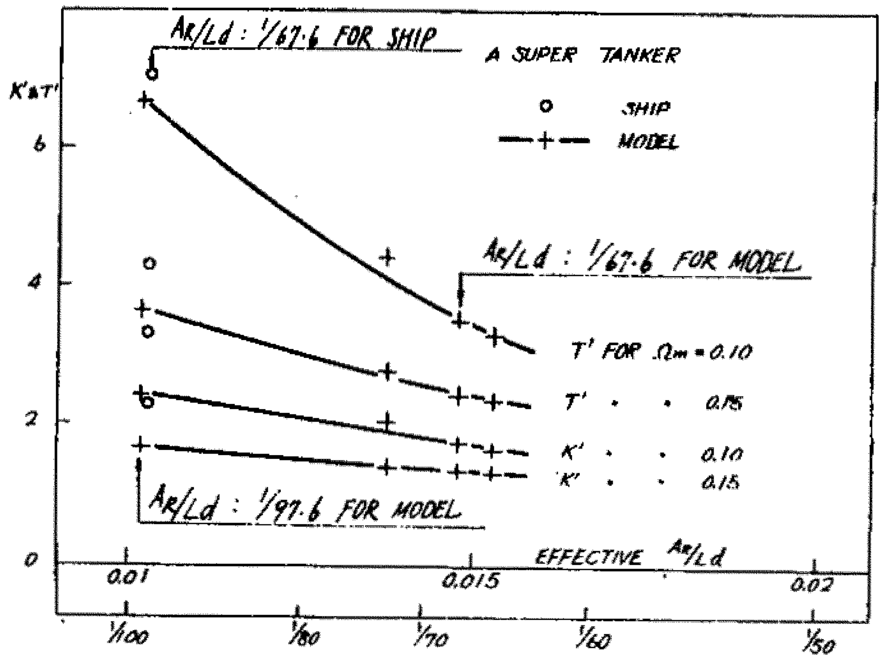

Fig. 6 MANOEUVRABILITY MODEL-SHIP CORRELATION WITH REFERENCE TO EFFECTIVE RUDDER AREA RATIO FOR A SUPER-TANKER.

According to the results, K' and T' values both for the ship and model seem to be fairly correlated on the basis of "effective rudder area ratio" (not of geometric A / Ld, however), so it may be fairly asserted that the model-ship discrepancy when running nearly straight may depend largely upon the difference in propeller loading between the two and the correlation may be much improved by developing some means to carry on model experiments so as to give the same rudder effectiveness as that for a corresponding actual ship. To use a model rudder of a reduced size that is estimated to yield the same relative rudder force may be one way. The leftmost model points in Fig.6 were obtained by this and model-ship correlation seems to be much improved.

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