2. A Study on the Instability Criterion of the Manual Steering of Ships

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Summary

A proposal to specify the permissible instability in the manual steering of ships was made in this paper.

It had been considered that ships should be course stable to be steered by human operators. However, our experience shows this concept is true only in the case of small ships. In the case of large ships, which are usually course unstable, it is not so difficult to steer them. Then, our new problem is to find the criterion how ships can be unstable in order to be steered by human operator without excessive difficulty. In addition, the criterion should hopefully be applied for any size of ship.

The concept of "Phase to be Compensated" was employed in this study to specify the instability criterion. This concept was of course deduced from the Nyquist stability criterion in the control theory.

According to this concept, the behaviour of human operators can be explained reasonably well and the difficulty in steering of any size of ships can be expressed on the same basis.

Several important conclusions were obtained by simulator studies:

(1) "Phase to be Compensated" should be less than 30 degrees.

(2) Human operators select the cut-off frequency of the feed-back loop at the most favourable point when they steer unstable ships.

(3) The time constant of steering gears must be small enough for small size vessels.

1. Introduction

Among full-bodied ships constructed in recent years, generally, inferiority in course stability is remarkable. The increase in number of unstable ships throws the question from a view point of ship design: What is the limit of instability of ships? Considering the complex and various aspects of ship operation, it seems to be quite difficult to answer globally this question, and to be necessary to collect multi-field researches. It is more actual to limit the problem to the basic aspects of operation.

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In this paper a proposal of the instability criterion in course keeping is discussed. The system in course keeping should be treated as closed-loop control consisting of a steering gear, a ship, a compass and a controller such as an auto-pilot or a human operator. The ability of the controller dominates the results in course keeping. In this paper, course keeping by a human operator is dealt, but the same idea may be expanded to the case of an auto-pilot.

The several patterns of course keeping by a human operator are known: bang-bang control, bang-bang with zero control and linear control[1]. A method to provide the limit of course in stability in the case of bang-bang control was already proposed[2)-3)]. This method is based on the idea that an unstable ship, when she is kept on a straight course, maintains a small amplitude self-exciting oscilation of heading angle. The controllable range of ships' characteristics can be calculated from the rudder period, yawing amplitude and threshold of yaw rate perceptible by a human operator.

Linear control (PD control) is a kind of steering methods, which is often used under stormy weather or when accuracy is required on the course deviation. Bang-bang control and bang-bang with zero control can be both regarded as "quantumized linear control". Thus there remains much generality to consider the human behaviour under course keeping as linear control. Therefore in this paper the discussion is based on this linear control.

Under course keeping the behaviour of a ship and a steering gear can be also regarded as linear, so the total system will be linear. In a linear system, the first consideration to be tried is stability criterion. There are many ways in stability criterion, but it is reasonable to take notice on phase relation in the case of course keeping by a human operator. Because it is very difficult to change his own phase characteristics, though the gain constant can be easily changed, taking advantage of power-driving steering system.

In this paper, first, phase characteristics of unstable ships are investigated. Secondary, control characteristecs of a human as a controller is analysed using the results of simulator experiments. Connecting the above results, the characteristic of course keeping of unstable ships by a human pilot is verified and the close relation with easiness of course keeping and phase lag of the controlled objects, a ship and a steering gear, is pointed out. Last, the results of simulator experiments in course keeping are shown to be well arranged by the idea of phase lag.

2. Control Problem of Unstable Ships

Generally, the directional control system of ships can be drawn as in Fig. 1. In the theme of this paper, the controller in the system is a human operator. The characteristic of a helmsman is seldom known even today. But as for other elements most are known.

Yawing motion of ships, if it is not so large, can be expressed satisfactory by Nomoto's 2nd order response function. That is

$$S(j\omega)=\frac{\dot{\psi}(j\omega)}{\delta(j\omega)}=\frac{K(1+j\omega T_3)}{(1+j\omega T_1)(1+j\omega T_2)} \quad (1)$$

A compass is a kind of an integrator and the characteristics of a steering gear can be

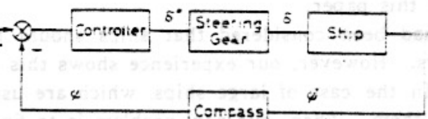

Fig. 1 Block diagram of the course control system

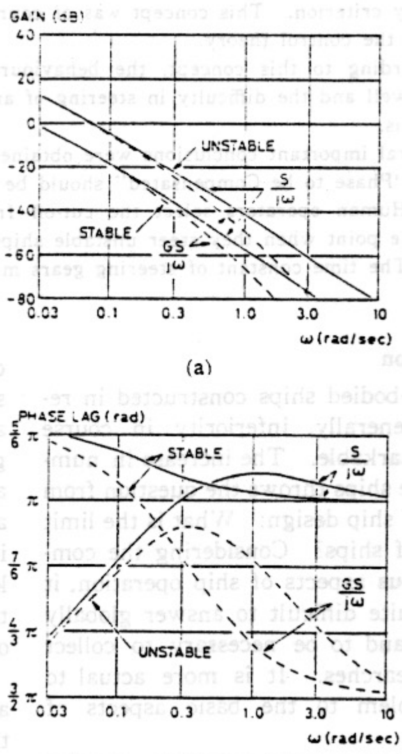

Fig. 2 Difference between stable and unstable ships in the gain and phase characteristics

described as follow, neglecting the speed limit of a rudder:

$$G(j\omega)=\frac{\delta(j\omega)}{\delta^*(j\omega)}=\frac{1}{1+j\omega T_E} \quad (2)$$

Let us compare the response characteristics of unstable ships with stable ships. Stable ships possess all positive values of K, T_1, T_2 and T_3. But in cases of unstable ships, K and T_1 are negative and generally the order is $|T_1|>T_3>T_2$. The gain and phase characteristics of them are compared in Fig. 2. The full lines in the figures denote ships' characters. Between stable ships and unstable ships they differs not so large in gain but quite large in phase. In cases of stable ships, phase lag grows from $\pi/2$ and reaches to π according to the increase of frequency. But in cases of unstable ships, it starts from $3\pi/2$ and settles to π. In usual unstable ships, as T_3 is larger than T_2, so that T_3 acts for decreasing phase lag and if the absolute of T_1 is adequately larger than T_3, phase lag once comes across π and again converges to π, as ω grows.

One of the methods of stability criterion is an idea of phase margin. In this method, at the cut-off frequency where the gain of the loop transfer function (loop gain) is 1, if the phase lag of the loop transfer function is below π, the system is judged stable (cf. appendix). Therefore in cases of stable ships, proportional control can make the system stable without any relation with the cut-off frequency, if the phase lag of a steering gear is neglected. Even if in cases of unstable ships, if the degree is not so inferior and then the absolute of T_1 is rather larger than T_3, there is the region where phase lag is smaller than π. If the gain is adjusted so as that the cut-off frequency exists within this region of frequency, the system will become stable only by proportional control. As described in introduction, considering the phase compensation is not always easy in course keeping, this fact is much appreciated. The degree of instability of ships, however, increases, where the absolute of T_1 decreases and approaches to T_3,

Table 1 Examples of the time constant of steering gears

Ships	T_E (sec)
Coast Guard Cutter	1.20
Car Ferry	2.29
do.	1.26
Container Carrier	2.00
V.L.C.C.	1.30
do.	2.90
do.	2.72
do.	1.15

phase lag of a ship increases and in any region of frequency it does not come across π. For these ships the system is unstable unless phase compensation is given by differential control.

The phase characteristics of the system has a close relation with the easiness of course keeping of ships, as mentioned above. As a consequence, the lag of a steering gear is also important. Table 1 shows examples of time constant T_E of steering gears. Besides, there is a speed limit which is decided by the capacity of a pump etc, as well as the time constant. The lag is restricted by the rule and has little variation among ships. In this paper, T_E is dealt as 2.5~3 seconds. In cases of large ships the phase lag by this time constant is negligible, though in cases of small ships the lag cannot be neglected because of a little difference between T_E and T_2. The broken lines in Fig. 2 show the transfer characteristics including the steering gear and the phase lag is always over π through any frequency. As the phase lag of ships' response increases, the controller should compensate equivalent.

From the above discussions, the phase angle to be compensated by the controller to stabilize the system seems to be a useful parameter in evaluating the easiness of course keeping. The phase angle to be compensated may be fixed by the following items:

(i) How much is the absolute of T_1 larger than T_3?

(ii) How much is the rate of T_3 and T_2?
(iii) How much is T_E smaller than T_2?

3. Characteristics of a Human Operator under Course Keeping

Characteristics of controlled objects in the closed-loop system is verified, so the characteristics of a human as a controller will be revealed. First, as described in introduction, we can point out that the gain characteristics is comparatively easy to change. From a view point of a human operator, it can be realized by handling the wheel a little bit more or less. Of course, from a ship's side, it means the increase in works of a steering gear, when the gain increases, but the power necessary is not so large and there remains few problem.

Contrary, it is not easy to adjust phase. It is said that human ability of differential control loses the ability under the existence of disturbances and that little advance in phase of steering is given. Phase advance derived by a human pilot, which will be discussed later, is limited. Therefore the problem is how a human operator can keep the course of an unstable ship, although he can give only a limited advance in phase.

Here, we should point out that a helmsman can adjust his own characteristics according to the nature of the controlled object. It is natural to consider even in ship's course control, a human operator adjust his control by trial and-error method and remember the way when he can control well and after then he keeps the way of steering. In fact, Nomoto *et al.* pointed out that a helmsman becomes skillful in course keeping according to the increase of training period from the simulator study[1].

How good a human operator control the course, then? To answer that it is necessary to observe the way of steering actually. For this purpose the investigation of a human control is carried out through the sumulation of course keeping using the simulator of Hiroshima University.

Ships used for the simulation are all unstable ships and their indices are listed in Table 2. The couple of numbers used to identify ships means L/V (sec.) (the former number) and full width of unstable loop (the latter). Phase characteristics of these ships are shown in Fig. 3. Full lines indicate the characteristics of each ship response and broken lines are also including that of a steering gear. In the simulation, disturbance as shown in Fig. 4 is added. Disturbance in the low frequency means wind disturbance and that in the higher range does noise induced by wave. The detail process of the noise assumption may be refered in[4]. This disturbance is supposed to be equivalent noise for a large full-bodied ship under the sea condition of the wind blowing at 16 meters per second, and it is rather large. This disturbance is selected so as to identify a human characteristics more effective, because human control becomes PD control when disturbance is large.

Control behaviour of a human does not obey a fixed rule of control just as in cases of

Table 2 Steering parameters for the simulation models

Ship	L/V sec	$2^*\delta_e$ deg	K sec^{-1}	T_1 sec	T_2 sec	T_3 sec	T_E sec	θ_e* rad
A10-4	10	4	−0.219	−51.9	3.20	8.0	3.0	0.106
A10-10	10	10	−0.104	−26.3	do.	do.	do.	0.242
A10-20	10	20	−0.057	−15.9	do.	do.	do.	0.387
A40-4	40	4	−0.055	−207.6	12.8	32.0	do.	−.201
A40-10	40	10	−0.026	−105.2	do.	do.	do.	−.107
A40-20	40	20	−0.014	−63.6	do.	do.	do.	−.001

* Phase angle to be compensated

machines, but for a simple treatment of analysis, it is convenient to introduce the helmsman's model as in Fig. 5[5,6]. $H(j\omega)$

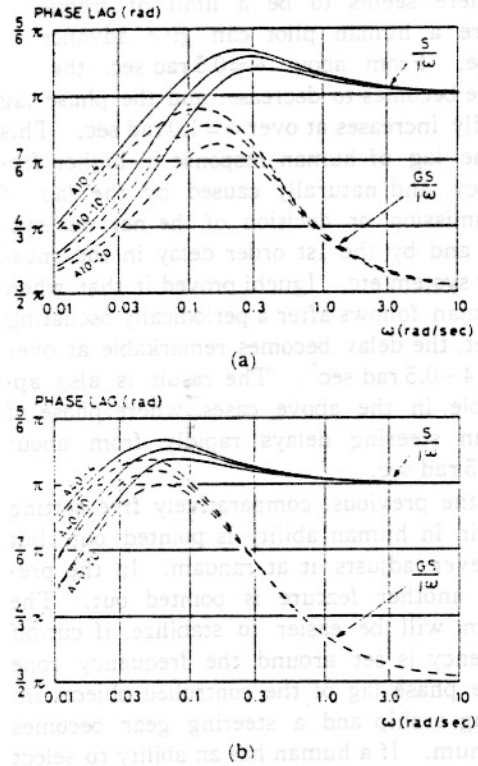

Fig. 3 Phase characteristics of the simulation models

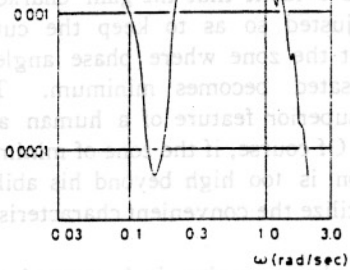

Fig. 4 A noise spectrum for the simulation

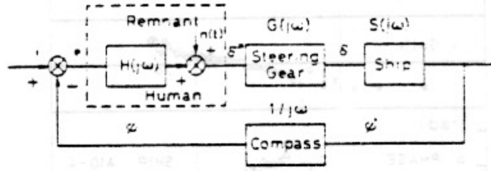

Fig. 5 The concept of helmsman's model in a course control system

is extracted to be an averaged linear control and the remainder is $n(t)$, which is the undescribable part in terms of $H(j\omega)$ and called as a remnant. $n(t)$ is regarded as a kind of noise, which is secondary from the principle of control.

It is generally difficult to obtain the describing function of a helmsman in a closed-loop system as Fig. 5, but if disturbance acting to the ship is regarded as an input of the system, a method of analysis utilizing randamness of disturbances can be of use. Cross-spectrum density of disturbance $i(t)$ and output of a human pilot can be expressed as follow:

$$\Phi_{i\delta^*}(j\omega)=\frac{H}{1+GS\cdot H}\Phi_{ii}(j\omega)+\frac{1}{1+GS\cdot H}\Phi_{in}(j\omega)\,, \qquad (3)$$

where

$\Phi_{ii}(j\omega)$: auto-spectrum density of disturbance $i(t)$,

$\Phi_{in}(j\omega)$: cross-spectrum density of remnant $n(t)$ and disturbance $i(t)$,

$H(j\omega)$: describing function of a human pilot,

and

$GS(j\omega)$: multiplied response function of a ship, a steering gear and a compass.

In the same manner, cross-spectrum density of disturbance and course deviation $e(t)$ can be described as,

$$\Phi_{ie}(j\omega)=\frac{1}{1+GS\cdot H}\Phi_{ii}(j\omega)-\frac{GS}{1+GS\cdot H}\Phi_{in}(j\omega)\,. \qquad (4)$$

Considering there is no relation between the

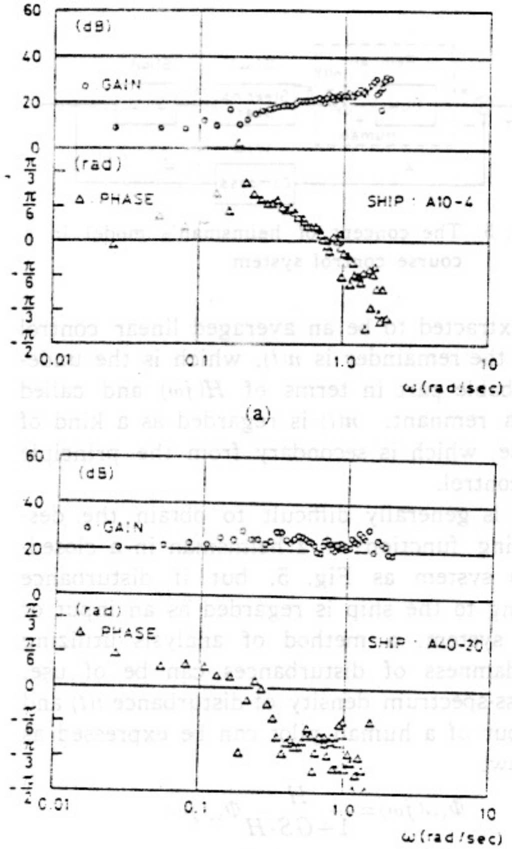

Fig. 6 An example of the quasi-linear transfer function of helmsman

remnant and the disturbance.

$$\Phi_{in}(j\omega)=0\ ,$$

then describing function of a human pilot can be calculated in the following form:

$$H(j\omega)=\frac{\Phi_{i\delta}(j\omega)}{\Phi_{ie}(j\omega)}\ . \qquad (5)$$

Fig. 6 shows examples of describing function obtained by this method and they are well settled. This method is quite useful to obtain the human characteristics. From the results, it is observed that the gain is quite different according to ships' L/V. On the other hand, the tendency of phase is not simple. With a survey of many other results of the simulation, it is supposed that phase compensation given by a human pilot is about $\pi/6$, and about $\pi/3$ in the maximum. Although further investigation is necessary, the value of $\pi/6$ would be a standard.

There seems to be a limit of frequency where a human pilot can give advance phase. From about $\omega=0.5$ rad/sec, the advance becomes to decrease, and the phase lag rapidly increases at over $\omega=1.0$ rad/sec. This is the lag of human response in higher frequency, and naturally caused by the lag of transmission or decision of the nervous system, and by the 1st order delay in the muscular system etc. Iguchi proved it that when a human follows after a periodically-oscilating turget, the delay becomes remarkable at over $\omega=0.4\sim0.5$ rad/sec[7]. The result is also applicable in the above cases, where phase of human steering delays rapidly from about $\omega=0.5$ rad/sec.

In the previous, comparatively free setting of gain in human ability is pointed out, but he never adjusts it at randam. In the previous another feature is pointed out: The system will be easier to stabilize, if cut-off frequency is set around the frequency zone where phase lag of the controlled objects including a ship and a steering gear becomes minimum. If a human has an ability to select his control behaviour according to the nature of the controlled objects, he is sure to utilize this fact with or without consciousness. Fig. 7 proves it. In the figures, the circles and the triangles show the gain and the phase characteristics of the system transfer function respectively and full lines show the gain and the phase characteristics of the system excluding a human pilot. In most cases of the figures, it is evident that the gain characteristics is adjusted so as to keep the cut-off frequency at the zone where phase angle to be compensated becomes minimum. This shows the superior feature of a human as a controller. Of course, if the zone of minimum compensation is too high beyond his ability, he cannot utilize the convenient characteristics of a ship.

From the above results, it is proved that

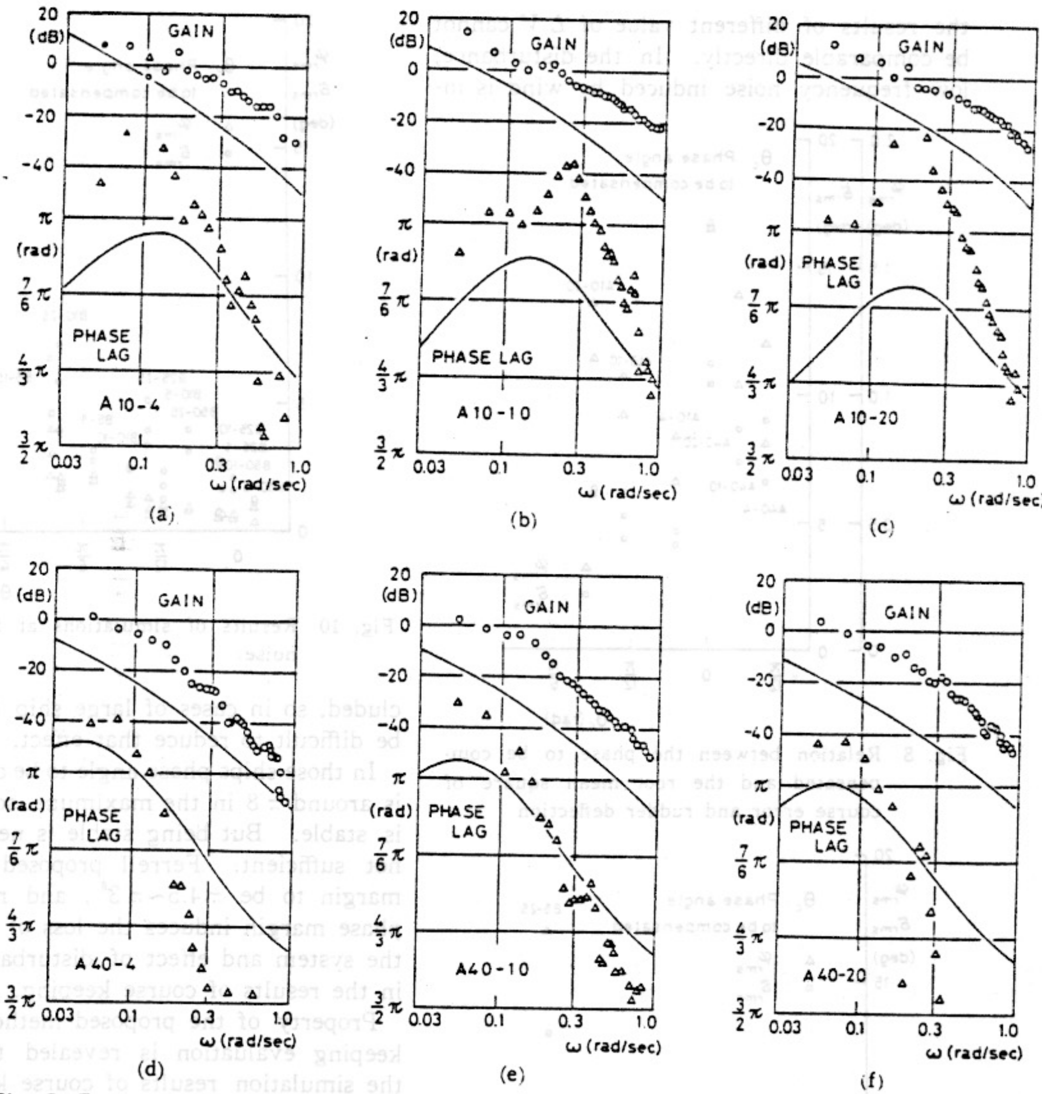

Fig. 7 Examples of the loop gain and phase lag of course control system under manual steering

the easiness of course keeping by a human operator is mainly dominated by the phase angle to be compensated to stabilize the system at the frequency where he can adequately follows after.

4. Phase Characteristics and Results of Course Keeping of Ships

As the feature of course keeping of unstable ships by a human operator is found clearly, the results of course keeping simulation should be arranged on this basis. Fig. 8 shows thus arranged data of course deviation and rudder angle in the base of phase angle to be compensated. Simulation was conducted for cases of L/V=10 sec. and 40 sec., and the results have obviously a close relation with phase angle to be compensated for each L/V. As the phase compensation required to a human increases, the results of course keeping are getting worse. Because the same disturbance is used both for large ships and small ships, the results of different value of L/V cannot be comparable directly. In the disturbance, low frequency noise induced by wind is in-

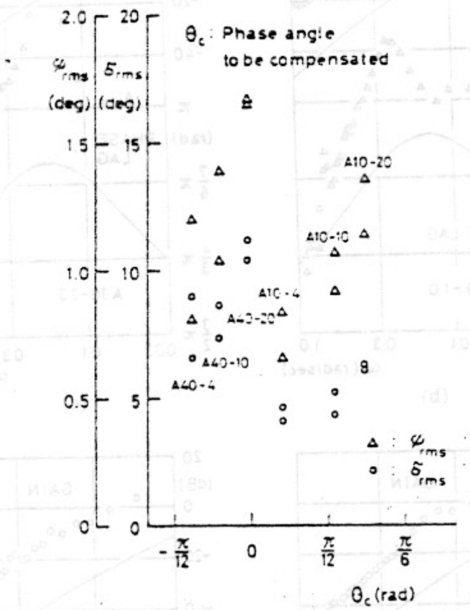

Fig. 8 Relation between the phase to be compensated and the root mean square of course error and rudder deflection

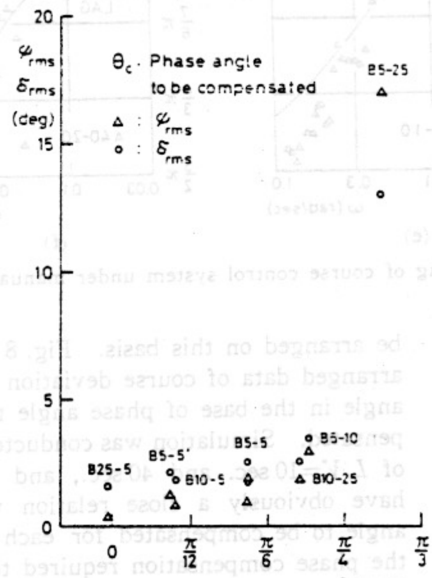

Fig. 9 Results of simulations at SR·151 (without noise)

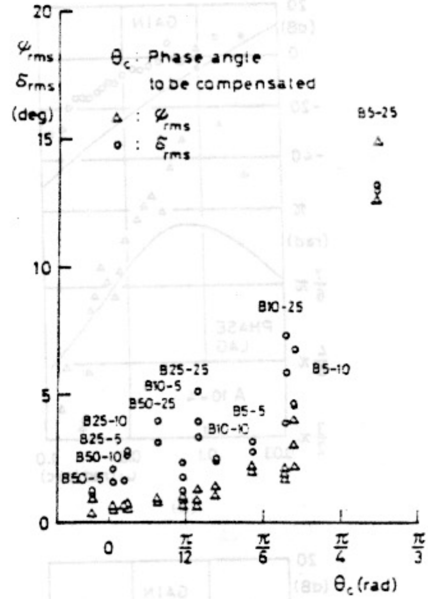

Fig. 10 Results of simulations at SR·151 (with noise)

cluded, so in cases of large ship it seems to be difficult to reduce that effect.

In those ships phase angle to be compensated is around $\pi/8$ in the maximum, so the system is stable. But being stable is necessary and not sufficient. Ferrell proposed the phase margin to be $\pi/4.5 \sim \pi/3$[8], and reduction of phase margin induces the loss of damping in the system and effect of disturbance appears in the results of course keeping.

Property of the proposed method of course keeping evaluation is revealed typically in the simulation results of course keeping carried out by Nomoto *et al.* in the project of the 151th Committee of the Shipbuilding Research Association of Japan (SR151). The detail of the experiments are fully reported in its report[4], and the results are picked up in Fig. 9 and Fig. 10. In the ships used for the simulation, phase angle to be compensated includes also the value from $\pi/5$ to $\pi/3.5$, and they are over $\pi/6$ which is the maximum phase compensation given by a helmsman. In fact, it looks almost impossible to keep the course of ships whose angle to be compensated is over $\pi/6$.

The disturbance used for this simulation is smaller than that of Hiroshima University and contains only comparatively higher frequency component. In such cases the steering pattern of a human pilot is almost bang-bang or bang-bang with zero control. But this method of evaluating course keeping derived from the concept of linear control seems to be available also in cases of such controls.

5. Conclusion

What is the limit of human ability to keep the course of unstable ships? Authors have discussed about the above question and the conclusions obtained are as follows:

(1) A human pilot would give phase advance as possible, and adjust his own gain so as to set the cut-off frequency at the zone of least phase lag of controlled objects, when he keeps the course of an unstable ship.

(2) Maximum phase advance given by a human operator is around $\pi/6$, and if the phase lag of a ship including a steering gear becomes over $(7/6)\pi$ within the frequency range of $\omega \leq 0.4$ rad/sec, it becomes difficult to keep the course.

(3) It is effective to improve course controllability to reduce the time constant of a steering gear especially in the cases of smaller ships.

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Appendix

Stability Criterion of Feed-back System of Unstable Ships

Let the loop transfer function be G. We note that the system transfer function is $1/(1+G)$ and that the poles of $1/(1+G)$ are equal to zeros of $1+G$. If all zeros of $1+G$ have negative real parts, the system is absolutely stable. Nyquist's method is to test such zeros using the transfer function. This is a test for the existence of roots in the right-hand half of the $[Z]$ plane.

A clockwise travel along the right-half plane of $[Z]$, as shown in Fig. A-1, will be mapped on $[G]$ as the transfer function in the range of $\omega = -\infty \sim +\infty$. Let the number of the clockwise revolutions around the point $(-1, 0)$ in $[G]$ be N, which is the difference of zeros and poles of $1+G$ in the right-half plane of

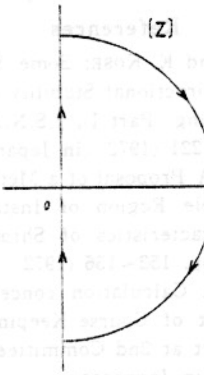

Fig. A-1

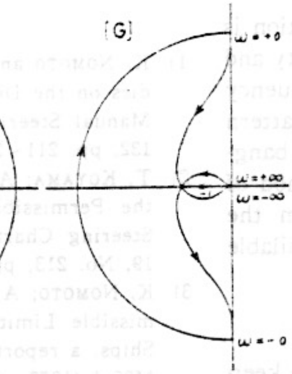

Fig. A-2

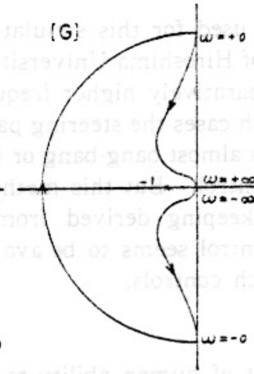

Fig. A-3

$[Z]$. Considering the poles of $1+G$ coincide with the poles of G, the number of poles can be treated as a known value. So that we can get the number of zeros in the right-half plane of $[Z]$ by N.

In cases of unstable ships, as the transfer function has one pole in the right-half plane of $[Z]$, the conformal mapping of G should make one anti-clockwise revolution around the point $(-1, 0)$ as shown in Fig. A-2 in order to make the feed-back system stable. This corresponds to the fact that phase lag is less than π at the frequency where the loop gain is 1. If the phase lag is over π as shown in Fig. A-3, the transfer function rotates one time clockwisely around the point $(-1, 0)$, which is connected with two zeros in the right-half plane of $[Z]$ and the feed-back system becomes unstable. To prevent it phase lag should be less than π by means of phase compensation.