“MARSIM 2000” Conference Proceedings (May 8-12,2000 Orlando, USA)
International Conference on Marine Simulation and Ship Maneuvering

CRITERIA FOR YAW-CHECKING AND COURSE-KEEPING ABILITIES IN IMO’s INTERIM STANDARDS FOR SHIP MANOEUVABILITY

Yasuo Yoshimura, Sumitomo Heavy Industries Ltd., Yokosuka, Japan
Kuniji Kose, Hiroshima University, Higashi-Hiroshima, Japan
Tomihiro Haraguchi, Ship Research Institute of Japan, Mitaka, Japan

Abstract

International Maritime Organization (IMO) adopted the interim standards for ship manoeuvrability A751(18) in 1993 for preventing the marine disasters. These standards cover the typical manoeuvrability including turning ability, course-keeping and yaw-checking ability and stopping ability. As these standards, however, were not settled under the sufficient manoeuvrability data, it was noted that they should be reviewed and finalised after practical experiences. For this purpose, the Ministry of Transport of Japan has been gathering the many trial data for these 5 years, and pointed out that the criteria regarding to course-keeping, yaw-checking and stopping abilities have some problems in the practical application to the actual ships [IMO DE35 INF.14].

In this paper, the authors review the manoeuvrability standards particularly focussing the criteria for the course-keeping and yaw-checking abilities in the present interim standards. Firstly, the indices for these abilities are discussed. Then, the criteria are evaluated based on the many trial data as well as theoretical and simulator studies. Finally, some proposals are summarised for the revise of the interim manoeuvrability standards.

1. Introduction

Recent maritime disaster of a large tanker often causes serious oil pollution. To prevent such disaster, the interim standards for ship manoeuvrability A751(18) was adopted in IMO. It is applied to the ships of 100 m in length and over, and every chemical tanker and gas carrier. It is also required to gather the sufficient data and information for the time being, and the standards should be reviewed after 5 years of experience. The present interim standards are shown in Table 1. They cover turning ability, initial turning ability, stopping ability and course-keeping, yaw-checking ability.

Table 1. Present criteria in IMO’s interim standards.

ABILITY	TEST	CRITERIA	
Turning ability	Turning test with max. rudder angle	Advance <4.5L Tact. Dia. <5.0L	
Initial Turning ability	10°/10° Z-test	Distance ship run before 2nd rudder execution < 2.5L	
Stopping ability	Stopping test with full astern	Track reach < 15L	
Course-keeping and Yaw-checking ability	10°/10° Z-test	1st Ovs.<10°	(L/U<10s)
		<5°+0.5L/U	(10s< L/U<30s)
		<20°	(30s<L/U)
		2ndOvs.<25°	(L/U<10s)
		<20°+0.5L/U	(10s< L/U<30s)
		<35°	(30s<L/U)
	20°/20° Z-test	1st Ovs.<25°	

Among these abilities, the criteria of turning ability and initial turning ability are evaluated to be very reasonable from the database studies by Kose et al [1]. For the criteria of course-keeping, yaw-checking and stopping abilities, the Ministry of Transport of Japan presented that there are some inconsistencies and problems in the practical application to the actual ships based on the many recent trial data.

In case of the course-keeping and yaw-checking abilities, the present standard employs three different indices. The limiting levels of the manoeuvring performance are quite different in each other [2]. The limit set on the 2nd overshoot of 10° Z-test is the most severe. The 1st overshoot of 20° Z-test's is moderate and the 1st overshoot of 10° Z-test is the least restrictive in general. The important point is the evaluation for these criteria whether reasonable or not. In such point of view, the authors try to investigate the indices and their criteria for these abilities, using many trial data and theoretical analysis.

2. Indices for Course-keeping and Yaw-checking Abilities

Firstly, the indices for course-keeping and yaw-checking abilities are summarised here. These studies provide theoretical and experimental foundation for the discussion of the standard.

2.1 Indices for Course-keeping Ability

Course-keeping ability is the ship performance how easily keeps a course. It depends on the directional stability of ship. The response of rudder to yaw-rate is described by the following Nomoto’s formula [4].

$$T_1T_2\dddot{\varphi}+(T_1+T_2)\ddot{\varphi}+\dot{\varphi}=K(\delta+T_3\dot{\delta}) \qquad \text{-------------------- (1)}$$

where, δ: rudder angle,

φ: yawing angle of ship,

and every coefficients in the equation : T_1T_2, (T_1+T_2) and K are proportional to the following stability index $(1/D)$

$$D=Y_\beta(-N_r)-(m+m_x-Y_r)\,N_\beta \qquad \text{------------------- (2)}$$

where, Y_β, N_β, Y_r, N_r are the linear hydrodynamic derivatives acting on ship hull.

When the value of D is positive large, the course-keeping ability becomes very well, and negative large value very worse. This is the principle of course-keeping ability, however the D can not be evaluated from conventional sea-trials, because the ship motion is produced by the balance of rudder’s exciting force and ship’s damping force. As the results, the index for course keeping is more or less affected by the rudder turning force.

As for the practical indices, the spiral characteristic, i.e., spiral loop width or loop height obtained from spiral or reverse spiral tests, overshoot of heading angle or time to yaw-check of course-change or Z-test can be pointed out. These indices are demonstrated in Figure 1. The spiral loop width and loop height increase when the static gain K in the eq.(1) becomes negatively small by means of large negative D. Meanwhile, the overshoot and time to yaw check increase when the time constants T_1, T_2 in the eq.(1) become large by means of decrease of D. Although these static and dynamic characteristics seem to be apparently different in each other, it is noted that they come from the same stability index D.

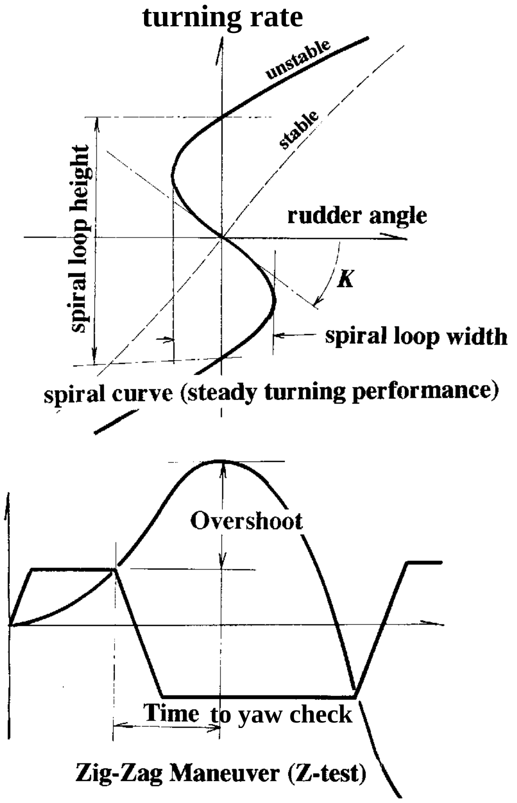

Figure 1. Examples of indices for course-keeping ability

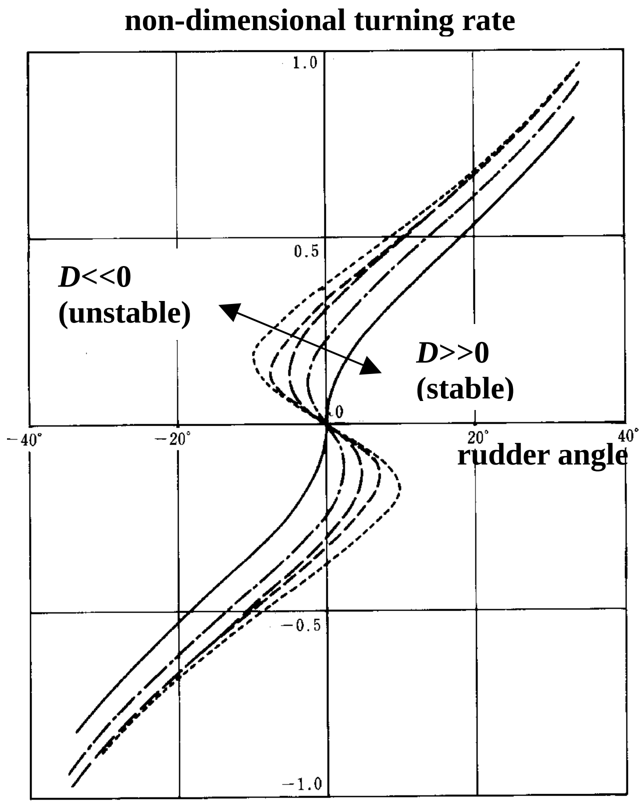

Figure 2. Simulated spiral curves for different directional stability

As for the index of standard, the following factors should be also considered.

(1) index has a clear and physical meaning.

(2) easy to carry out the test to obtain the indices.

(3) easy to measure the indices.

The spiral loop width or the spiral loop height has been widely used at the ship designing stage. They comes from spiral test, reverse spiral test or pullout manoeuvre at sea trials. Figure 2. shows the simulated spiral curves for different directional stability, where the increase of loop width can be seen as decrease of directional stability *D*. The overshoot heading angle or time to yaw-check at course changing is often used in actual navigation for checking the ship's response to rudder. However, it must be noticed that these practical indices are more or less affected by the rudder effectiveness as mentioned above.

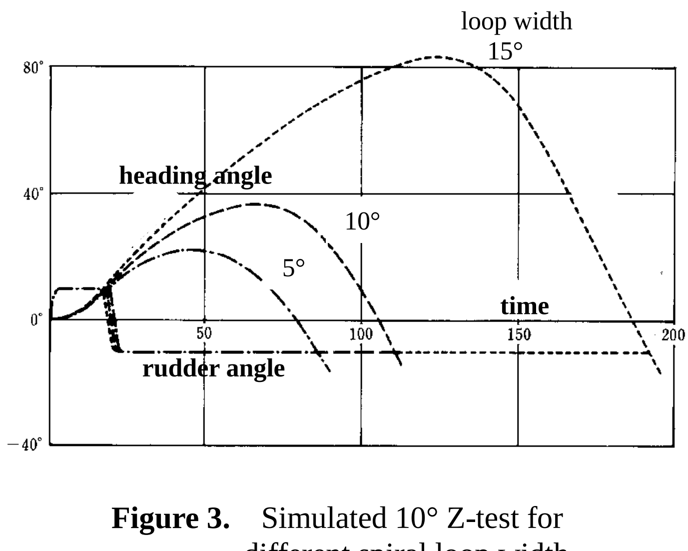

Figure 3. Simulated 10° Z-test for different spiral loop width

2.2 Indices for Yaw-checking Ability

Yaw-checking ability is the ship performance how fast defeats the turning motion and settles the course. As for this criterion, the overshoot or time to yaw-check of course-change or Z-test must be suitable. For the relation between overshoot and time to yaw-check, 10° Z-test is simulated in Figure 3. with ships that have different spiral loop width. From this figure, it is clear that the larger loop width makes the larger overshoot and time to yaw-check, and the close relation can be seen between overshoot and time to yaw-check.

This means that the overshoot can also express the time lag of steering response. When the overshoot is selected as the index of course-keeping ability, it represents both yaw-checking and course-keeping abilities. This would be better in the application of the standard.

2.3 Relation between 1st Overshoot of 10° Z-test and Spiral Loop Width

As mentioned above, it is desired that the index should be obtained directly from the sea trial. Spiral and reverse spiral test, however, require a wide waterway, considerable measuring time and the special devices to measure the turning rate in details. On the contrary, the 1st overshoot of 10° Z-test is very easy to do, so it was proposed as the index of course-keeping and yaw-checking abilities [3],[5]. This idea was come from the fact that the shipmaster can empirically recognise the ship's manoeuvrability from the effectiveness of the check helm or the overshoot during a course change. The check helm angle is usually less than 15°. The measurement as well as execution of the 1st overshoot is very simple and easy by means of just watching the navigation compass.

The relation between spiral loop width and the 1st overshoot of 10° Z-test can be obtained numerically simulating Z-test with varying the directional stability. The obtained relation is shown in Figure 4. together with the measured data in actual ships. From this figure, the 1st overshoot of 10° Z-test can express the spiral loop width.

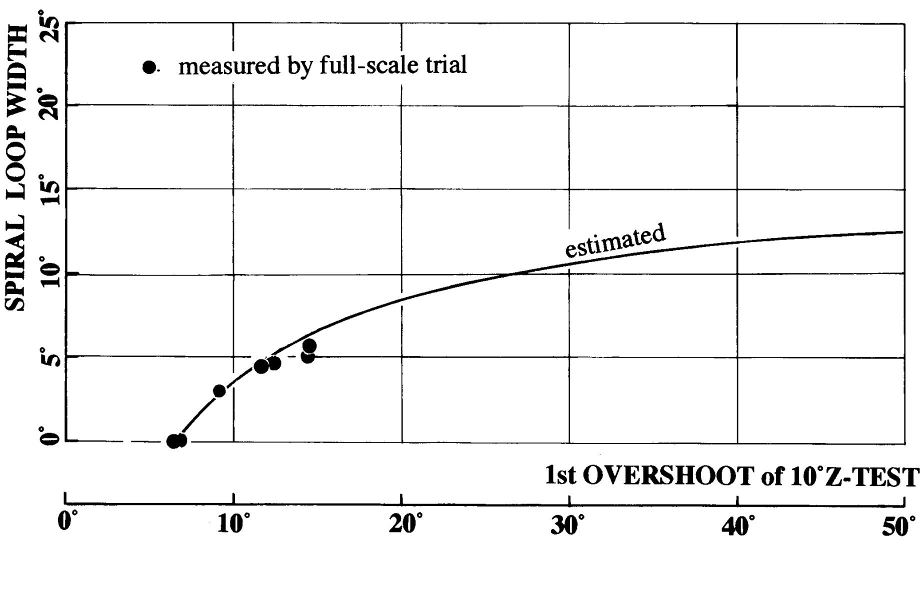

Figure 4. Relation between spiral loop width and 1st overshoot of 10° Z-test

3. Criterion for Course-keeping and Yaw-checking Ability

3.1 Result from Actual Ship's Research by Japanese Marine Pilots

According to the research of the Japanese Pilots' Association [3], the 1st overshoot of 10° Z-test and manoeuvring difficulty were gathered with approx. 30 actual ships. All of the ships were navigated in such a manner that they sailed at almost a constant speed in the congested Inland Sea route of Japan, and there was no stage at which a tugboat was used. The degree of manoeuvring difficulty was evaluated as the following five levels. The judgement was left to the pilot:

score

(1) :Easy to manoeuvre.

(2) :Safe manoeuvring is possible in most cases without preliminary information

(3) :Safe manoeuvring is possible in most cases with preliminary information provided.

(4) :Safe manoeuvring is difficult even with preliminary knowledge provided.

(5) :Safe manoeuvring is not possible in almost every case of operation even with preliminary knowledge provided.

The collected data are plotted in Figure 5, and show the correlation between the degree of the manoeuvring difficulty perceived by the pilots and the measured first overshoot. Spiral loop width corresponding to the overshoot is also shown in the horizontal axis.

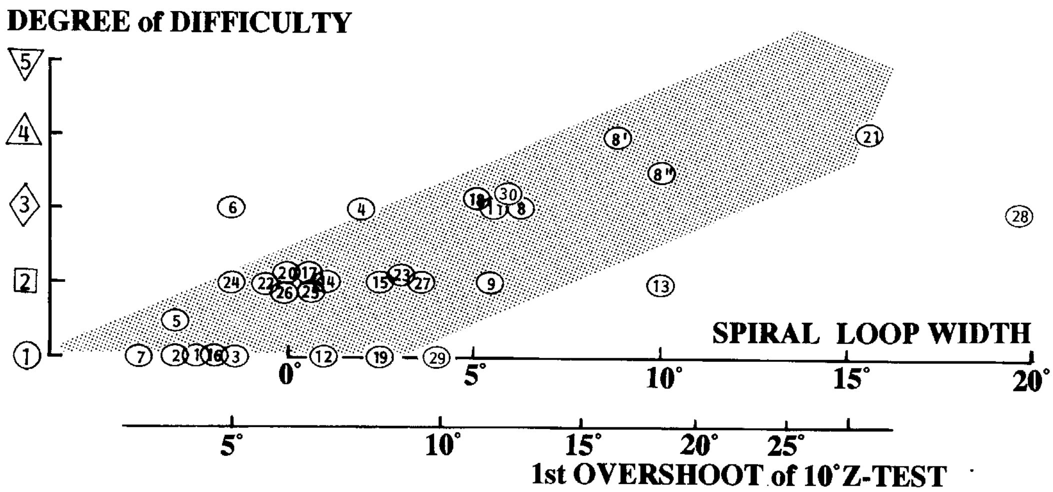

Figure 5. Relation between the actual ship's 1st overshoot and the degree of difficulty [3].

The stability of man-machine system is explained as the feedback control system consisting of ship, steering gear and human controller as shown in Figure 6. In order to stabilise this system, the loot locus of controlled object should not include (-1,0j) according to Nyquist's stability criterion as shown in Figure 7. In case of the unstable ship, however, the phase angle of transfer function of ship and steering gear has already lagged 180° or more.

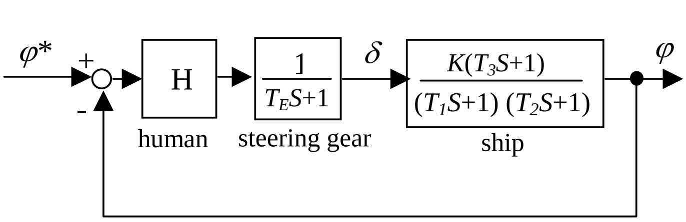

Figure 6. Block diagram of manual ship control system

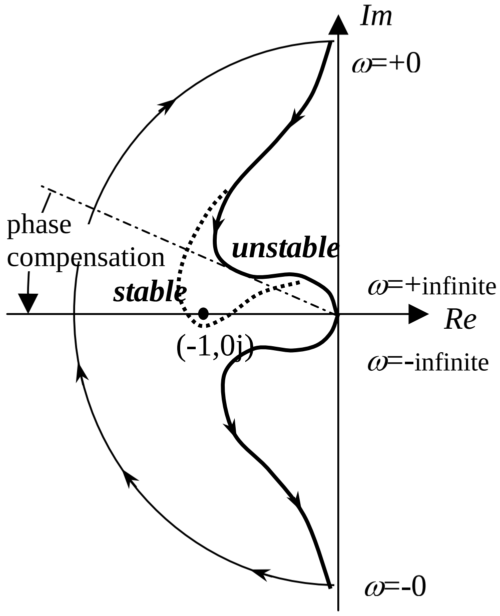

Figure 7. Loot locus of unstable ship and definition of phase compensation.

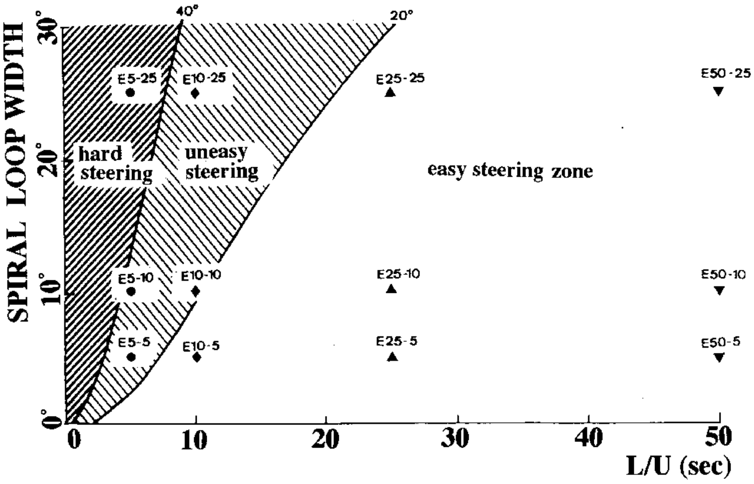

Figure 8. Map demonstrating ease of helmsman in manual course keeping [6]

So, it is necessary for the shipmaster and helmsman to reduce the phase lag as to be less than 180°. This phase angle is defined as phase compensation. According to Nomoto's course-keeping simulator studies [6], it is introduced that the phase compensation by a helmsman is limited to approx. 40° when strong efforts are made to maintain the course, and when 20° is exceeded, course-keeping become difficult. The helmsman's manoeuvrable zone has been defined as Figure 8. for various spiral loop width and (*L /U*). As the result, these characteristics surely correspond to Nyquist's stability criterion.

Similarly, the obtained scores are plotted as the map demonstrating in Figure 9. For the vertical axis of Figure 8., the 1st overshoot of 10° Z-test is employed together with spiral loop. The counter phase compensation curves on the rudder to yaw response are marked in this figure. It suggests that the

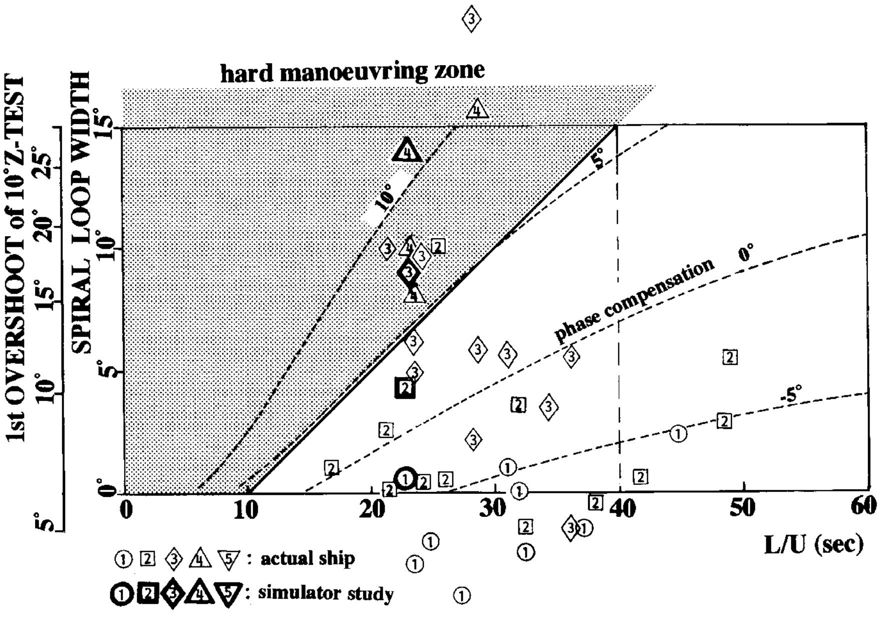

Figure 9. Map demonstrating ease evaluated by the marine pilots [3].

maximum phase compensation provided by the pilots can not exceed 5° from the viewpoint of man-machine control dynamics.

3.2 Result from Simulator Analysis

Previous results have been introduced mainly from the viewpoint of stability analysis. This map demonstrating ease permits the larger 1st overshoot in larger *L/U*. However, the limit of 1st overshoot of a large tanker with *L/U*=50 for example, permits 30° or more. This should be examined. According to the Kose's simulator studies in a restricted waterway [7], the following facts are pointed out. When the 1st overshoot of 10° Z-test or loop width exceeds the certain level, the ship handling becomes difficult even if the phase compensation is still smaller. This tendency remarkably appears in the congested narrow waterway.

The results of these simulator studies are summarised as follows.

(1) The level of the allowable spiral loop width is decreased at the passing through a narrow waterway, because the pilot more frequently order the maximum rudder angle, and they perceive the more difficulty. As the results, it is required to maintain the sufficient margin in control device.

(2) The limit of spiral loop width in such situation is found to be 10° which corresponds to the first overshoot of approx. 20°

These results lead to the another limit of 1st overshoot as shown in Figure 10.

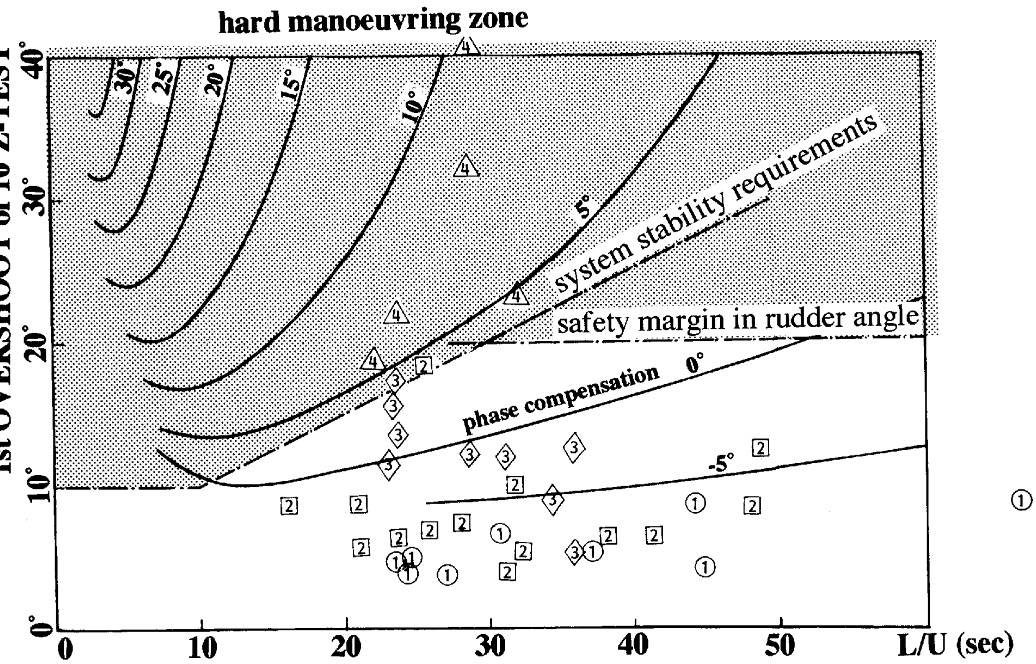

Figure 10. Proposed criterion for course-keeping and yaw-checking abilities, together with the ease of marine pilots [2]

3.3 Criterion for Course-keeping and Yaw-checking Abilities

The above mentioned researches have made clear that the level of the 1st overshoot of 10° Z-test or spiral loop width should be limited from the viewpoint of the man-machine control system. These studies provide the criterion for course-keeping and yaw-checking abilities using spiral loop width or 1st overshoot of 10° Z-test. For the purposes of the manoeuvrability standard, however, the spiral loop width is inconvenient due to the difficulties during on-board measurements, time-consuming procedure, measuring techniques particularly for the reverse spiral test. On the contrary, Z-test or course change is very easy to perform and the result can be converted to the spiral loop width as mentioned before. Therefore, the 1st overshoot of 10° Z-test was selected for the practical index of both yaw-checking and course-keeping abilities as shown in Figure 8.

Finally, the following criterion was proposed from Japan. This criterion was submitted to the DE committee in 1992 as the Japanese proposal. Then, it was adopted one of the criteria of course-keeping and yaw-checking abilities in the present interim standards.

L/U < 10 sec ------ 1st Ovs.< 10°
10 sec < L/U < 30 sec ---- 1st Ovs.< 10°+(L/U-10)/ 2 ---------------------------- (3)
30 sec < L/U ---- 1st Ovs.< 20°

4. The Other Criteria for Course-keeping and Yaw-checking Ability in the Present Interim Standards

As for the criterion for course-keeping and yaw-checking abilities, 1st overshoot of 10° Z-test is reasonable as mentioned above. In the present standard, however, the other two criteria were adopted simultaneously. One is the 2nd overshoot of 10° Z-test and the other is the 1st overshoot of 20° Z-test. The criterion of 1st overshoot of 10° Z-test has been introduces based on the theoretical and experimental researches. The other two criteria, however, are not clear nor have investigated yet.

4.1 2nd Overshoot of 10° Z-test

The 2nd overshoot of 10° Z-test is quite different from the 1st one. The 1st overshoot of 10° Z-test is the overshoot heading angle after heading angle is reached 10° from 0° straight running. On the contrary, the 2nd overshoot is that after heading angle is reached -10° from (10°+1st overshoot), as shown in Figure 11. Therefore, the 2nd overshoot becomes the yaw-checking ability to defeat the large turning motion that is produced during the heading angle is reached (20°+1st overshoot) from zero turning using 10° rudder angle. It becomes 30° even if the 1st overshoot is 10°. As the result, the 2nd overshoot has a tendency to be increased by this difference of the heading angle. In the present standard, 15° is considered as the increment of 2nd overshoot. However, the value is too small. As the result, this criterion becomes severe and unreasonable as described later. It should be properly examined as done with 1st overshoot. It may be necessary three times as large as the criterion in the present interim standard.

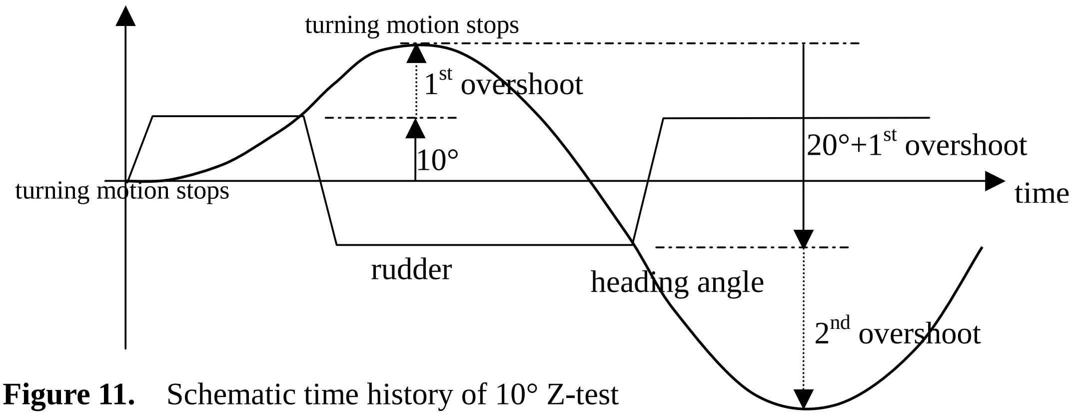

Figure 11. Schematic time history of 10° Z-test

4.2 1^{st} Overshoot of 20° Z-test

The 1^{st} overshoot of 20° Z-test has the same tendency as the 1^{st} overshoot of 10° Z-test. The overshoot of 20° Z-test may become twice larger than that of 10° in principle. On the other hand, the value is fixed 25° in the present standards. As the result, this criteria is advantage for the ships with L/U<12.5, but it becomes severe criterion for the large ships with L/U>12. This criterion is also unreasonable.

4.3 Comparison of the Criteria in the Present Interim Standards

Although the above differences may be reduced as the 1^{st} overshoot of 20° Z-test becomes smaller than the twice of 10° Z-test because of the increase of non-linearity in rudder to yaw response, the 1^{st} overshoot of 20° Z-test has the tendency as those of 1^{st} overshoot of 10° Z-test. For the comparison of the three criteria in the present interim standards, 1^{st} overshoot of 20° Z-test and 2^{nd} overshoot of 10° Z-test are displayed in Figure 12. converting to the same form of the 1^{st} overshoot of 10° Z-test [2]. The criterion of 2^{nd} overshoot of 10° Z-test is the most severe, and the 1^{st} overshoot of 20° Z-test is secondly severe. In order to examine this criterion, on-board investigation and simulator studies should be done.

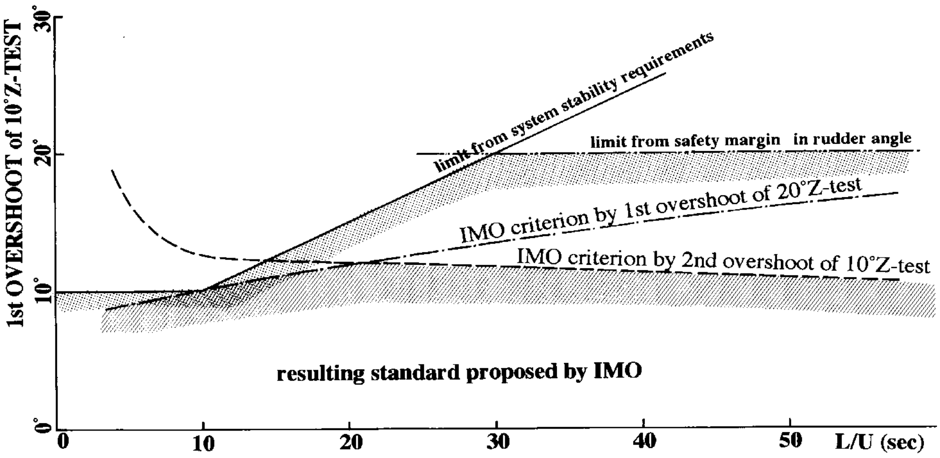

Figure 12. Comparison of three criteria in the present interim standard [2].

5. Investigation on the Resent Sea Trial Data

The Ministry of Transport of Japan has been gathering the trial data since A751(18) was settled. The number of gathered ships is over 280. From the data of about 50 ships in the full load condition, criteria for course-keeping and yaw-checking abilities are investigated below.

5.1 The 2^{nd} Overshoot of 10° Z-test

Figure 13. shows the results of sea trials on the 1^{st} overshoot of 10° Z-test, where several ships do not comply with this criterion. Figure 14. shows the results on the 2^{nd} overshoot of 10° Z-test, excluding the above sub-standard ships. In this figure, it can be seen that many ships do not comply with the 2^{nd} overshoot of 10° Z-test. However, these ships comply with the criterion of the 1^{st} overshoot of 10° Z-test (solid marks in Figure 13.). Besides, they have no reports that their manoeuvring performance was poor. These results show the present criteria of the 2^{nd} overshoot is unreasonable for the ships that have no problem with manoeuvrability.

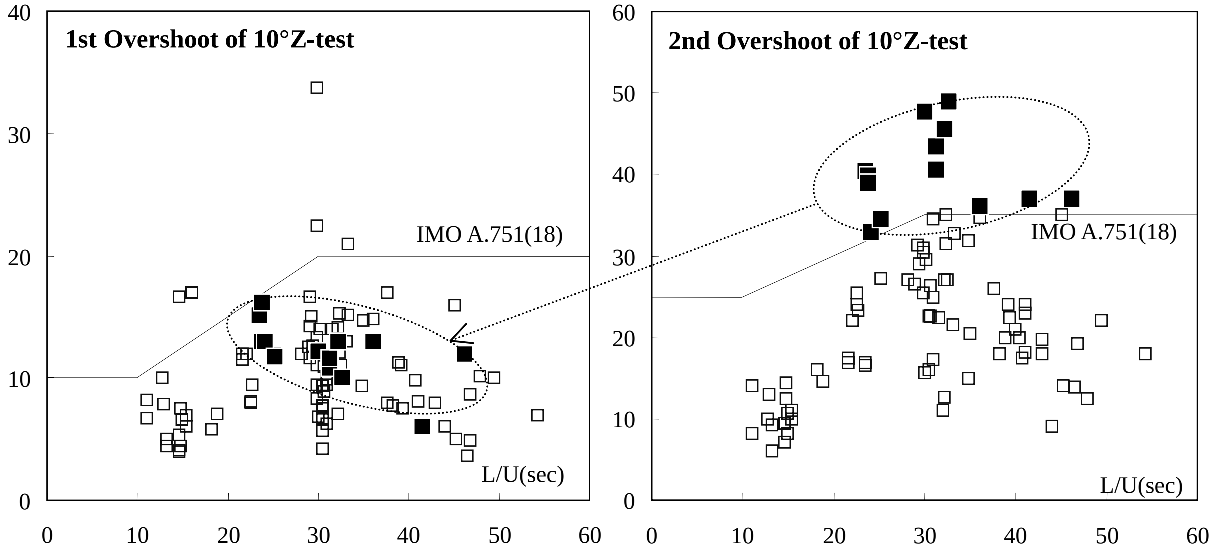

Figure 13. The 1st overshoot of 10° Z-test
L: ship length(m),
U: approach speed(m/s)

Figure 14. The 2nd overshoot of 10° Z-test [Excluding the data that do not comply with the criterion of 1st overshoot of 10° Z-test (Figure 13.)]

5.2 The 1st Overshoot of 20° Z-test

Figure 16. shows the results on the 1st overshoot of 20° Z-test, excluding the sub-standard ships, where it can be seen that several ships do not comply with the 1st overshoot of 20° Z-test. Although these ships with solid marks in Figure 16. satisfy with the criterion of the 1st overshoot of 10° Z-test,

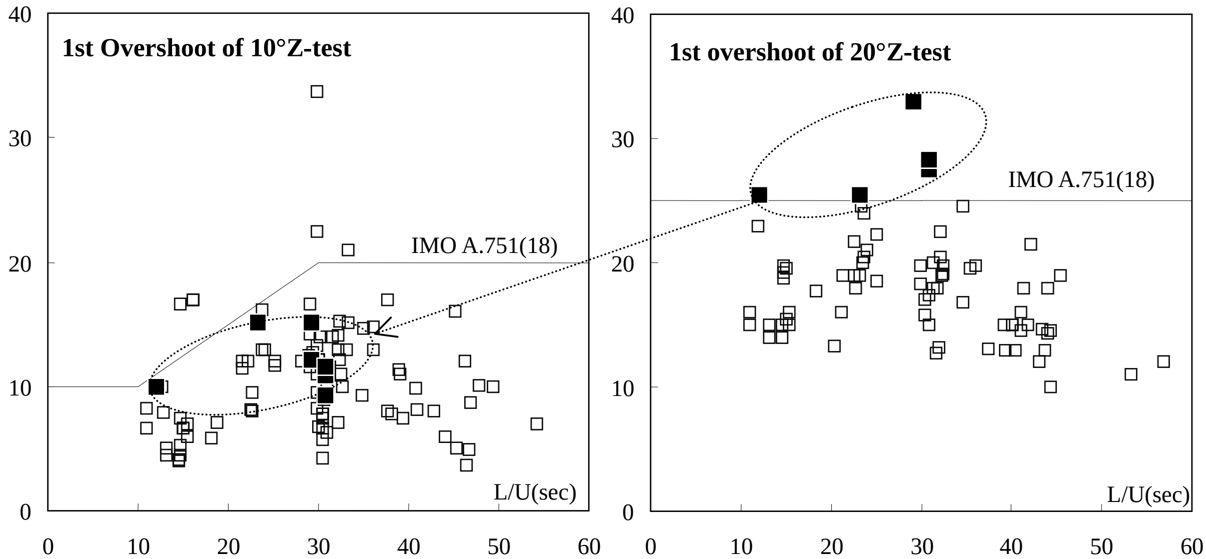

Figure 15. The 1st overshoot of 10° Z-test
L: ship length(m),
U: approach speed(m/s)

Figure 16. The 1st overshoot of 20° Z-test [Excluding the data that do not comply with the criterion of 1st overshoot of 10° Z-test (Figure 15.)]

the ships do not comply with the criterion of the 1st overshoot of 20° Z-test as shown in Figure 16. These figures also show that the present criterion of 20° Z-test is unreasonable for several ships.

6. Conclusions

The authors have reviewed the criteria of IMO's interim manoeuvrability standards particularly for course-keeping and yaw-checking abilities. The major concluding remarks are pointed out as the followings.

(1) The index for course-keeping ability is not easy to define, because the stability criterion can not be evaluated from conventional sea-trials. Since the ship motion is produced by the balance of rudder force and ship damping force, it must be affected more or less by the rudder effectiveness. As the practical index, 1st overshoot of Z-test as well as spiral loop width is suitable.

(2) For the index for yaw-checking ability, overshoot of Z-test can indicates this ability itself.

(3) From the full-scale investigation and simulator studies, the 1st overshoot of 10° Z-test that is one of the index of course-keeping and yaw-checking abilities is the best index. The criterion of the 1st overshoot of 10° Z-test can be determined based on the investigations of many sea trial data including ships with poor manoeuvring performances, as well as the results of the theoretical analysis and the simulator studies.

(4) On the other hand, the criteria of 2nd overshoot of 10° Z-test and 1st overshoot of 20° Z-test do not seem to be investigated well from experimental and theoretical points of view on the stage of decision of these criteria. Moreover, these criteria may regard the ships with good manoeuvring performance as them with poor manoeuvring performance. As the results, these criteria should be reconsidered and adjusted based on the theoretical and experimental data, if these criteria will be really applied.

This paper is accomplished regarding to the research of working group RR-74 in the Japan Ship Research Association. The authors would like to many thanks to the chairman Prof. Kijima as well as the members of the working group.

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