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A Simulator Study on Yaw-checking and Course-keeping Ability in IMO's Ship Manoeuvrability Standards

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Abstract

Yaw-checking and course-keeping ability in IMO's ship manoeuvrability standards is reviewed from the viewpoint of safe navigation. Three kinds of virtual series-ships, which have different course instability, are taken as test models. The numerical simulation on Z-test is carried out in order to examine the correlation between known manoeuvrability in spiral characteristics and various kinds of overshoot angle. Then simulator experiments are executed with series-ships in a curved, narrow waterway by five pilots in order to examine the correlation between known manoeuvrability and degree of manoeuvring difficulty. IMO criteria for yaw-checking and course-keeping ability are discussed and new criteria are proposed.

Keywords: IMO's ship manoeuvrability standard, yaw-checking ability, course-keeping ability, simulator study

1 Introduction

Recent marine disaster of large ships often causes serious oil pollution(Song 1993). To prevent or reduce such a disaster, International Maritime Organization(IMO) has been endeavoring to improve ship's manoeuvrability, and adopted the interim standards for ship manoeuvrability A751(18) in 1993(Kang 1993). These standards cover the typical manoeuvrability including turning ability, initial turning ability, yaw-checking and course-keeping ability, and stopping ability.

In this paper the authors review the manoeuvrability standards particularly focusing the criteria for the yaw-checking and course-keeping ability. Firstly, the authors take three ships built in Korea recently, from which they prepare the series-ships with systematically different spiral loop widths, and carry out numerical simulation on Z-test to examine the yaw-checking and course-keeping ability of the series-ships in terms of overshoot angles. Then, simulator experiment is carried out to grasp the correlation between known manoeuvrability and degree of manoeuvring difficulty felt by pilots. Finally, the IMO's standards are discussed, and new criteria are proposed and compared each to each in view of degree of manoeuvring difficulty.

2 Series-ships, mathematical model and overshoot angle of Z-test

2.1 Series-ships for calculation of overshoot angles

The authors take a training ship, a container ship and a bulk carrier as test models for the present study. Table 1 shows principal dimensions of three actual ships. In order to prepare three models of series-ships with different, systematic manoeuvrability, four linear hull derivatives are changed gradually for consideration of stern frame line, such as *U* or *V* shape of stern body plan(Yoshimura et al 1995), and simultaneously rudder area ratios are also changed gradually for consideration of profile effect at stern. Figure 1 shows stability index of hull only and rudder area ratio for preparation of three models of series-ships with different spiral loop width. Figure 2 shows simulated spiral curves of three models of series-ships with various spiral loop widths from 0 to 10 degrees at intervals of 2.5 degrees.

Table 1: Principal dimensions of original actual- ships

		Training ship (3,700 GT)	Container ship (4,300 TEU)	Bulk carrier (207,000 DWT)
Length bet. per.	L(m)	93.0	274.0	300.0
Breadth	B(m)	14.5	32.25	50.0
Depth	D(m)	7.0	21.7	25.7
Draft	d(m)	5.2	13.5	18.0
Block coef.	C_B	0.604	0.65	0.8388
Design speed	V($knots$)	15.0	23.5	13.5
L/V		12.0	22.7	43.2

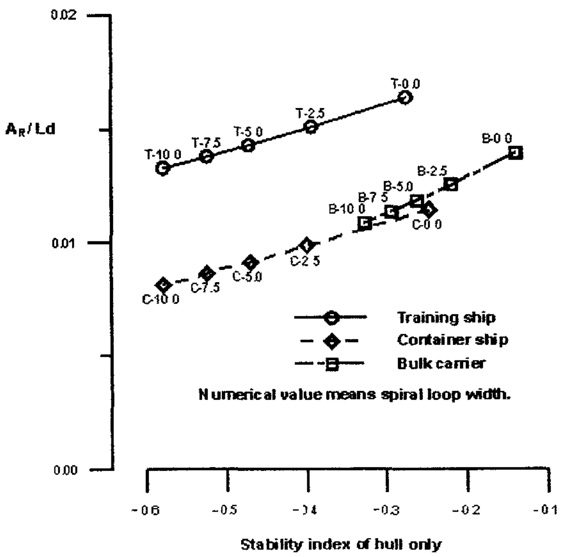
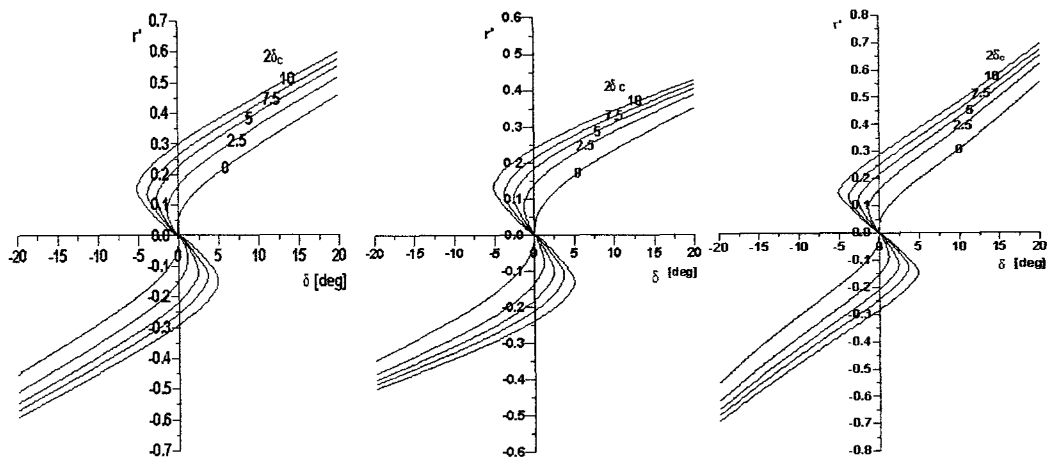


Figure 1: Rudder area ratio and stability index for generation of series-ships with systematically different spiral loop widths



(a) Training ship (b) Container ship (c) Bulk carrier

Figure 2: Spiral curves of series-ships with different spiral loop width : $2\delta c$

2.2 Mathematical model for simulation

In this paper the modular type mathematical model is employed for prediction of manoeuvrability in numerical simulation and simulator experiment as well. The mathematical model is summarized as follows. Following the sign convention of Figure 3, the basic equation of manoeuvring motion can be written as

$$\begin{aligned} m(\dot{u} - vr - x_G r^2) &= X \\ m(\dot{v} + ur + x_G \dot{r}) &= Y \\ I_{zz}\dot{r} + m x_G(\dot{v} + ur) &= N \end{aligned} \tag{1}$$

where m denotes ship's mass, I_{zz} moment of inertia about z axis, u and v velocities of ship in x and y directions respectively, r angular velocity of ship about z axis, the dot over parameters of ship motion time derivative, x_G distance of the centre of gravity in front of midship, X and Y hydrodynamic forces in the x and y directions respectively, and N hydrodynamic yawing moment about midship. If the added mass and added moment of inertia are taken into account and modular-type model, such as MMG model, is employed, Equation (1) will be expressed as follows.

$$\begin{aligned} (m + m_x)\dot{u} - (m + m_y)vr - (m x_G + m_y \alpha)r^2 &= X_H + X_P + X_R + X_W \\ (m + m_y)\dot{v} + (m + m_x)ur + (m x_G + m_y \alpha)\dot{r} &= Y_H + Y_P + Y_R + Y_W \\ (I_{zz} + J_{zz})\dot{r} + (m x_G + m_y \alpha)\dot{v} + m x_G ur &= N_H + N_P + N_R + N_W \end{aligned} \tag{2}$$

where the terms with subscripts H , P , R and W represent damping forces on hull, propeller forces, rudder forces and wind forces respectively. m_x and m_y denote added mass in the x and y directions respectively, J_{zz} added moment of inertia about z axis, and α the distance of the centre of m_y in front of midship. In order that current force may be taken into consideration, u and v are assumed to be relative velocity to water particle. Then u and v are expressed in terms of absolute velocity components of ship and current velocity as follows.

$$\begin{aligned} u &= u^* + V_c \cos(\psi_c - \psi) \\ v &= v^* + V_c \sin(\psi_c - \psi) \\ \dot{u} &= \dot{u}^* + V_c r \sin(\psi_c - \psi) \\ \dot{v} &= \dot{v}^* - V_c r \cos(\psi_c - \psi) \end{aligned} \tag{3}$$

where u^* and v^* denote absolute velocity described in space axes $\overline{O}-XYZ$ in Figure 3, V_c current velocity, and ψ_c current direction. Equations (2) and (3) give the following.

$$\begin{aligned} (m+m_x)\dot{u}^* &= (m+m_y)vr + (mx_G + m_y\alpha)r^2 - (m+m_x)V_c r \sin(\psi_c - \psi) \\ &\quad + X_H + X_P + X_R + X_W \\ (m+m_y)\dot{v}^* + (mx_G + m_y\alpha)\dot{r} &= -(m+m_x)ur + (m+m_y)V_c r \cos(\psi_c - \psi) \\ &\quad + Y_H + Y_P + Y_R + Y_W \\ (I_{zz} + J_{zz})\dot{r} + (mx_G + m_y\alpha)\dot{v}^* &= -mx_G ur + (mx_G + m_y\alpha)V_c r \cos(\psi_c - \psi) \\ &\quad + N_H + N_P + N_R + N_W \end{aligned} \tag{4}$$

One of the authors(Sohn 1992) proposed a mathematical model of hull damping forces at low advance speed with large drift angles as follows. The model originated and was modified from Takashina's experimental study(Takashina 1986).

$$\begin{aligned} X_H &= 0.5\rho L d V^2 \{X'_{uu}u' \mid u' \mid + X'_{vr}v'r'\} \\ Y_H &= 0.5\rho L d V^2 \{Y'_v v' + Y'_{ur}u'r' + Y'_{vv}v' \mid v' \mid + Y'_{vr}v' \mid r' \mid + Y'_{ur}u'r' \mid r' \mid\} \\ N_H &= 0.5\rho L^2 d V^2 \{N'_v v' + N'_{uv}u'v' + N'_r r' + N'_{vvr}v'^2 r' + N_{uvrr}u'v'r'^2 + N'_{rr}r' \mid r' \mid\} \end{aligned} \tag{5}$$

where ρ is density of water. L and d denote length between perpendiculars and mean draft respectively. And the parameters of ship motion and the hull damping forces are non-dimensionalised as follows.

$$\begin{aligned} & u' = u/V, \quad v' = v/V \\ & r = r \cdot L/V \\ & X'_H = X_H/0.5\rho L d V^2, \quad Y'_H = Y_H/0.5\rho L d V^2 \\ & N'_H = N_H/0.5\rho L^2 d V^2 \end{aligned} \tag{6}$$

In this model, the low advance speed effects are reflected on some terms in which u' is added. In case of normal advance speed, which is relatively high advance speed, the value of u' becomes almost 1.0, then (5) exactly coincides with Inoue model(Inoue et al 1981). Hirano(1992) also suggested the same mathematical model as (5) for practical prediction of manoeuvring motion at low advance speed. Expression of X_P , Y_P , N_P , X_R , Y_R , N_R , X_W , Y_W and N_W is referred to reference(Sohn 1997). Hydrodynamic derivatives and many other coefficients appearing in mathematical model can be obtained from a variety of references(Inoue et al 1981, van Lammeren et al 1969).

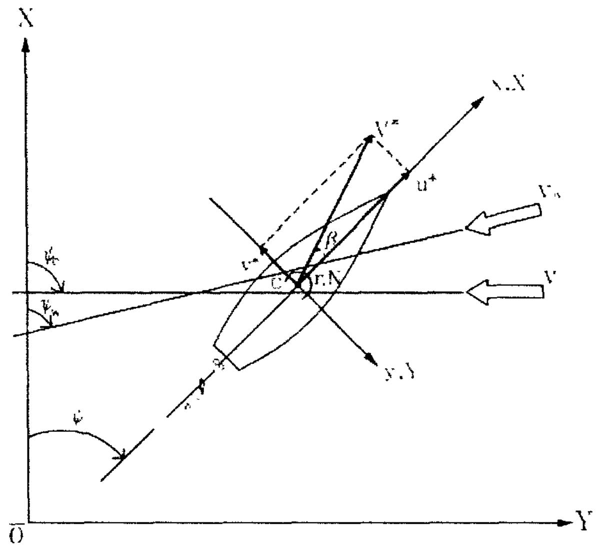


Figure 3: Coordinate system

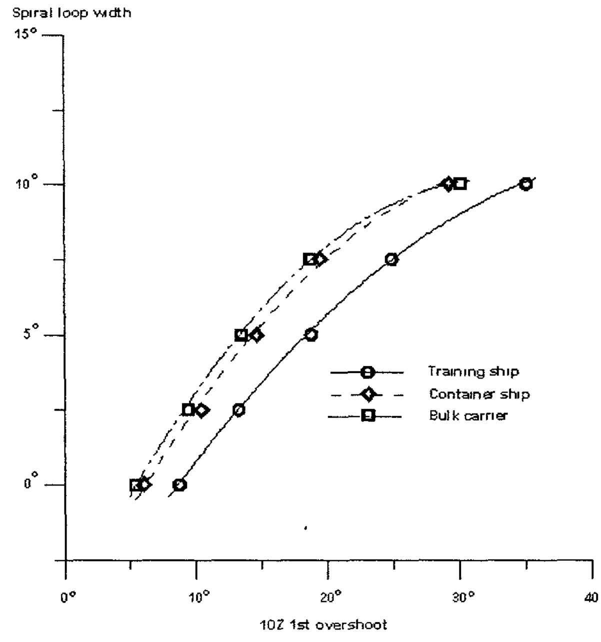


Figure 4: Relation between spiral loop width and the 1st overshoot angle of 10 degrees Z-test by numerical simulation

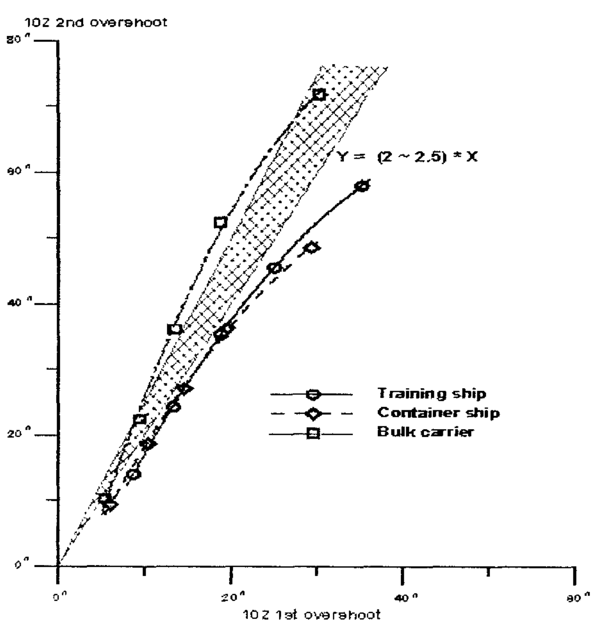


Figure 5: Relation between the 1st and the 2nd overshoot angles of 10 deg Z-test by numerical simulation

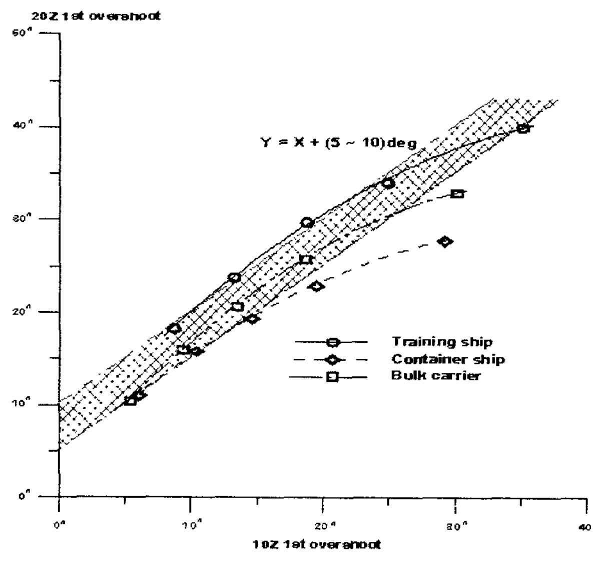


Figure 6: Relation between the 1st overshoot angle of 10 deg Z-test and the 1st overshoot angle of 20 deg Z-test by numerical simulation

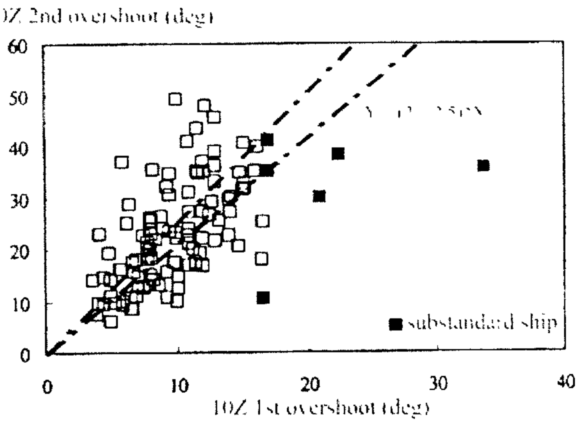


Figure 7: Relation between the 1st and the 2nd overshoot angles of 10 deg Z-test from sea trials database(Yoshimura 2000)

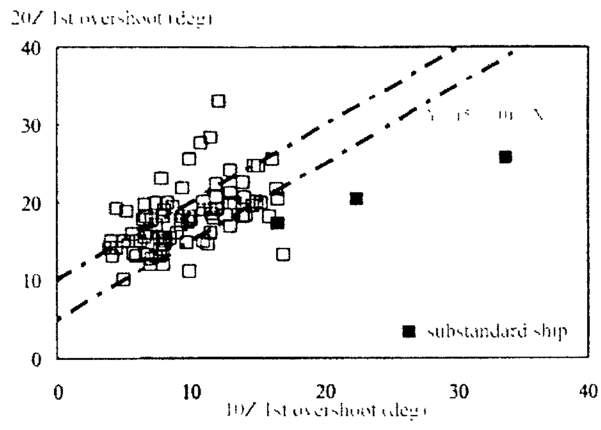


Figure 8: Relation between the 1st overshoot angle of 10 deg Z-test and the 1st overshoot angle of 20 deg Z-test from sea trials database(Yoshimura 2000)

2.3 Simulated overshoot angle of Z-test

Figures 4, 5 and 6 show the result of numerical simulation on Z-test. The initial speed of series-ship is the same as design speed of actual ship shown in Table 1. The simulation results show that the spiral loop width has strong correlation with the 1st overshoot angle of 10 degree Z-test. The 2nd overshoot angle of 10 degree Z-test is about 2 or 2.5 times larger than the 1st one of 10 degree Z-test, and the 1st overshoot angle of 20 degree Z-test is about 5 or 10 degrees larger than the 1st one of 10 degree Z-test. So the overshoot angle of Z-test can be well used not only as index of yaw-checking, but also as index of course-keeping ability. Figures 7 and 8 show the result of sea trials on the relation between overshoot angles of Z-test(Yoshimura 2000). The mean lines of the relation between overshoot angles agree with the present simulation, Figures 5 and 6.

3 Simulator experiment

The authors carry out simulator experiment in order to grasp correlation between overshoot angles provided in IMO's standards and the degree of manoeuvring difficulty felt by pilots. The shiphandling simulator has been constructed by the authors for this purpose. The schematic of system configuration for the present simulator is shown in Figure 9.

The situation of passing in a curved, narrow waterway is taken as simulation scenario. The authors select the east waterway of designated area of Inchon Harbour Approaches. Figure 10 shows the map of selected waterway. The depth of waterway is assumed to be deep enough. Wind and current are applied to ship as external forces. Wind velocity is considered as 10 m/sec from WNW(293^o) and current as 2 $knots$ to NE(050^o). One of the mission to shiphandling is passing along the waterway centerline as possible and the other is keeping propeller revolution constant as that of harbour full speed. Harbour full speeds are 12 $knots$ in training ship, 17.6 $knots$ in container ship and 10.8 $knots$ in bulk carrier respectively. Only rudder command is allowed and pilot issues the order to helmsman orally. Five ship operators participate in the simulator experiment. All of them are pilots on service in Korea, who have pilotage experience of one

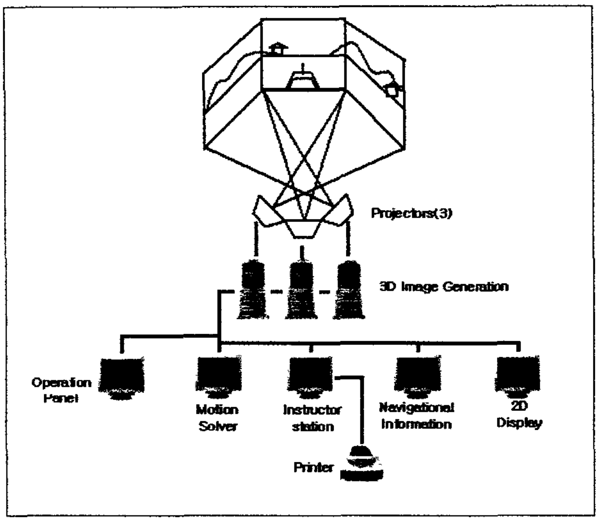


Figure 9: Schematic of system configuration for present simulator

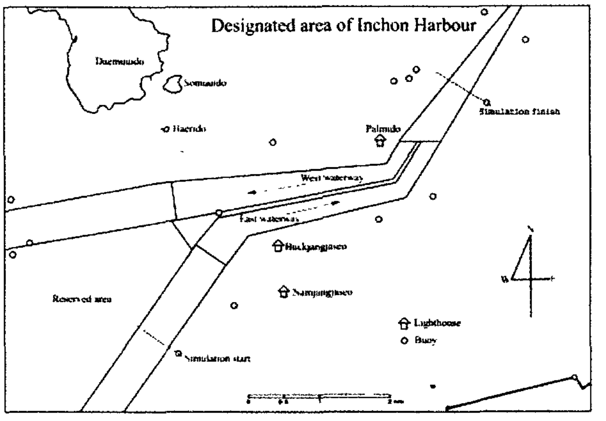


Figure 10: Map of waterway and Inchon Harbour Approaches employed for present simulator study

to five years after serving on merchant ships for about 10 years or more. Before the simulator experiment, brief explanation is given to pilots on purpose of experiment, tested ships, waterway, external environment, mission to shiphandling and so on. Simulator experiment is executed using three models of series-ships, such as training ship, container ship and bulk carrier series models. In case of same series model, the experiment is executed one by one in order of ship's instability on course, which means that the experiment of ship with small loop width is executed first.

Figure 11 shows averaged root-mean-square values of ship's lateral deviations from waterway centerline. Some differences in magnitude are appeared according to model of series-ships but no difference according to loop width of same series model. On the contrary, the lateral deviations of ships with large loop width are slightly smaller than those of ships with small loop width. It seems that familiarization with same model results in no difference in lateral deviation due to repeated simulation of series ships with different spiral characteristics. Figure 12 shows averaged root-mean-square values of applied rudder angles. Some differences in magnitude are appeared according to model of series-ships and also loop width of same model of series-ships as well. Applied rudder angles come to be larger in order of ratio of ship length to design speed (L/V) and ship's instability on course or loop width as well. Figure 13 shows degree of manoeuvring difficulty in terms of subjective evaluation rating scale felt by pilots. The authors employ three kinds of subjective evaluation item. They are skill required, difficulty of task and stress level felt by pilot during shiphandling simulation. Every evaluation item has 10 rating scales from 0 to 9. Larger rating scale means more skill required, more difficulty of task and higher stress level respectively. These rating scales are evaluated by pilots immediately after every execution of simulation. Figure 13 shows averaged values of three kinds of rating scale evaluated by five pilots concerning each ship. Averaged subjective evaluation rating scale has strong correlation with loop width. Figure 14 shows correlation between averaged subjective evaluation rating scale and averaged root-mean-square values of applied rudder angle during simulation. It is obvious that applied rudder angle is proportioned to subjective evaluation rating scale. But the magnitude

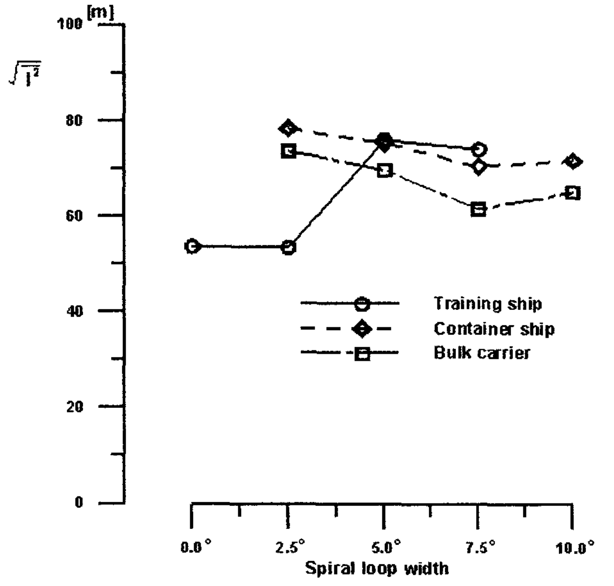


Figure 11: Averaged root-mean-square values of lateral deviations from waterway centerline during simulation

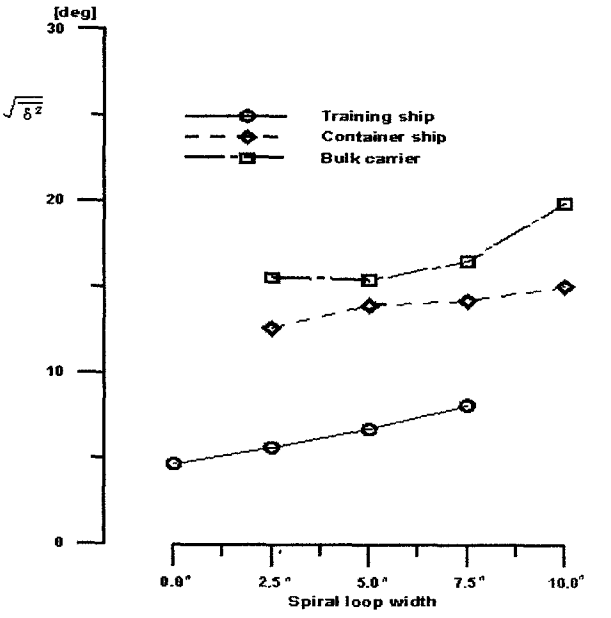


Figure 12: Averaged root-mean-square values of applied rudder angle during simulation

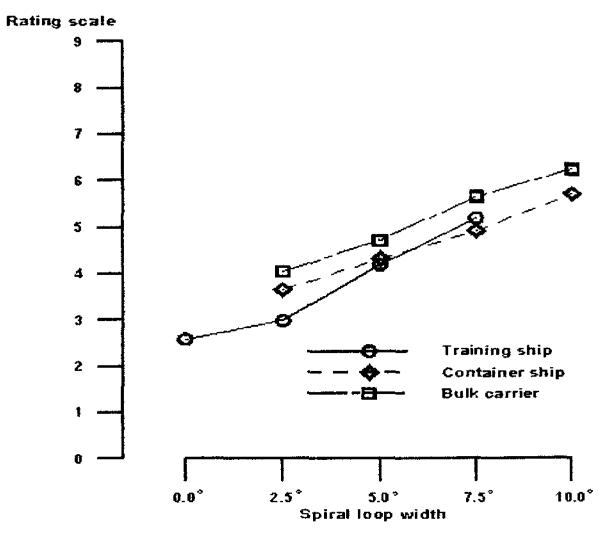


Figure 13: Averaged subjective rating scales evaluated by pilots during simulation

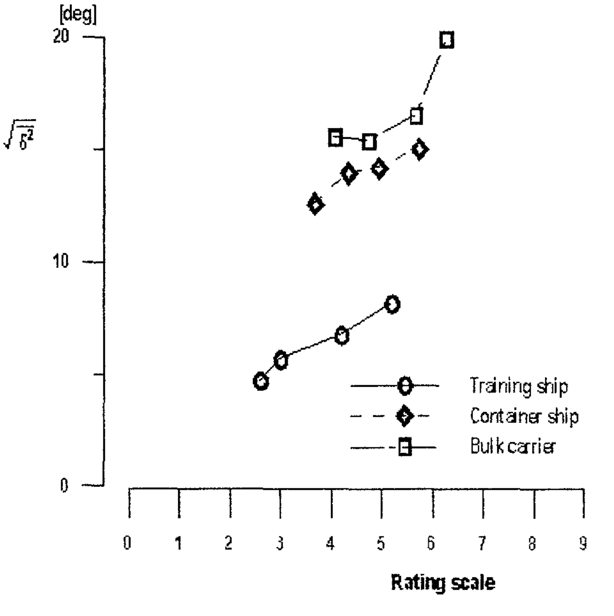


Figure 14: Correlation between averaged subjective rating scales and averaged root-mean-square values of applied rudder angles during simulation

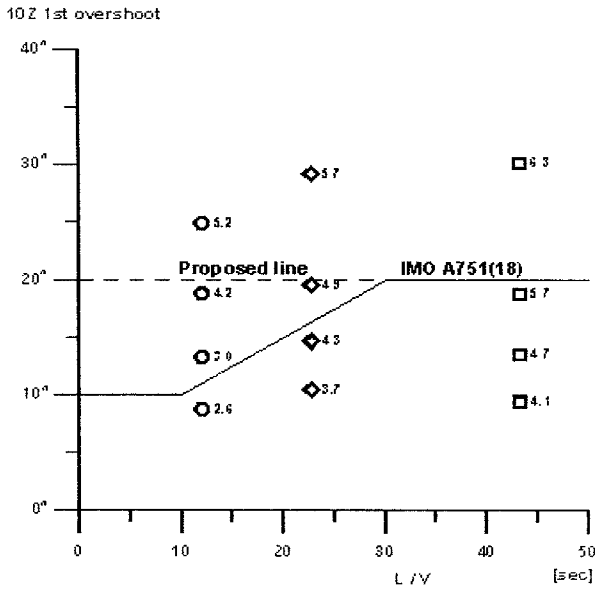


Figure 15: Averaged subjective rating scales marked on IMO's standard diagram(the 1st overshoot angle of 10 deg Z-test)

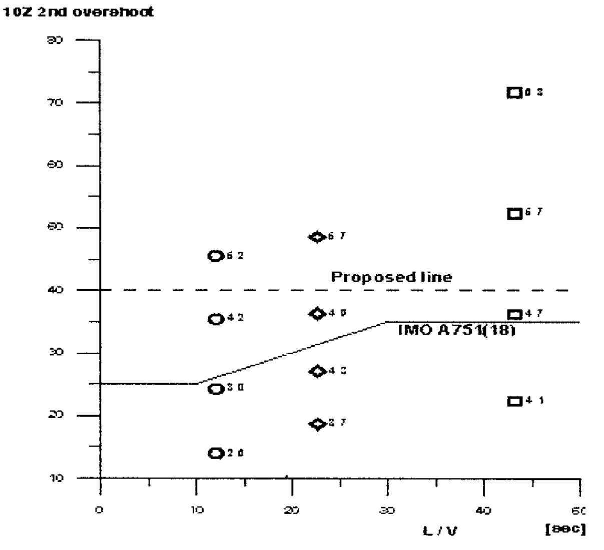


Figure 16: Averaged subjective rating scales marked on IMO's standard diagram(the 2nd overshoot angle of 10 deg Z-test)

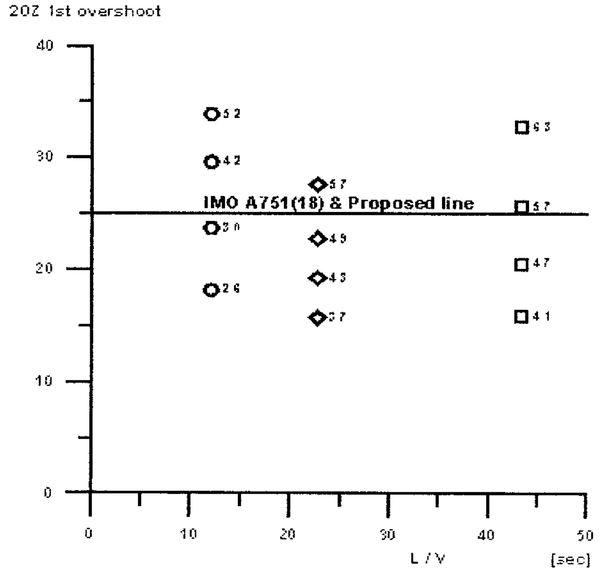


Figure 17: Averaged subjective rating scales marked on IMO's standard diagram(the 1st overshoot angle of 20 deg Z-test)

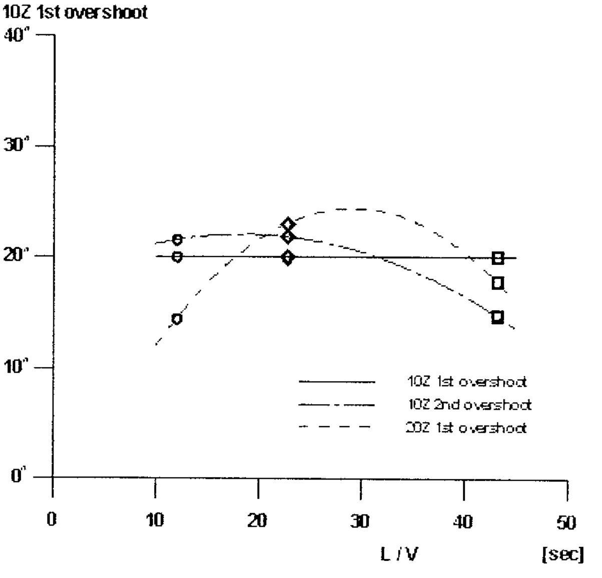


Figure 18: Comparison of three proposed criteria in terms of the corresponding 1st overshoot angle of 10 deg Z-test

of applied rudder angle is different with one another according to a model of series-ships. Figures 15, 16 and 17 show rating scale data by simulator experiment, marked on IMO A751(18) criterion diagram.

In Figure 15, the IMO criterion on the 1st overshoot angle of 10 degree Z-test was decided to different values along L/V in order to take the steering speed into consideration. However the simulator experiment shows that manoeuvring difficulty rather decreases as L/V decreases. So the authors propose 20 degree as the limit line of the 1st overshoot angle of 10 degree Z-test regardless of L/V values, which means almost 5 in rating scale. In Figure 16, the authors propose 40 degree as the limit line of the 2nd overshoot angle of 10 degree Z-test regardless of L/V values, which has been decided in consideration of rating scale 5 and also numerical simulation result on the relation between the 1st and the 2nd overshoot angles in 10 degree Z-test. In Figure 17, the authors propose the same value as that of IMO A751(18) in consideration of rating scale 5 and also numerical simulation result on the relation between the 1st overshoot angle of 10 degree Z-test and the 1st one of 20 degree Z-test. Figure 18 shows the comparison of three proposed criteria in terms of the corresponding 1st overshoot angle of 10 degree Z-test, which has been prepared from simulated result on Z-test(Figures 5 and 6). The comparison of three proposed criteria shows almost the same level in manoeuvring severity. The existing IMO criterion on the 2nd overshoot of 10 degree Z-test is too much severe, but the tendency has been reduced in the proposed criterion. Therefore the proposed criteria are thought to be more reasonable than existing IMO criteria. In addition, Figures 15, 16 and 17 reveal that even though spiral loop widths are the same, the rating scale values of bulk carrier(L/V 43.2) are larger than those of container ship(L/V 22.7) or those of training ship(L/V 12.0), which means that handling of ship with larger L/V, on the whole, is more difficult than that with smaller L/V. In other words, even though some large ships satisfy IMO's standards, pilots may feel difficult in passing through in curved, narrow waterway.

4 Conclusions

Through the simulator study using three models of series-ships with the different course instability, the authors have reviewed IMO's ship manoeuvrability standards particularly focussing the criterion for yaw-checking and course-keeping ability. As far as the present simulator study is concerned, the major concluding remarks are pointed out as follows.

(1) Overshoot angle of Z-test can be well used not only as index of yaw-checking, but also as index of course-keeping ability.

(2) Applied rudder angle during simulation has strong correlation with her instability on course and with subjective evaluation rating scale as well.

(3) New criteria on yaw-checking and course-keeping ability are proposed as Figures 15, 16 and 17 in view of degree of manoeuvring difficulty.

(4) Even though spiral loop widths are the same among three models of series-ships, handling of ships with larger length to speed ratio, on the whole, is more difficult than that with smaller length to speed ratio.

(5) Even though some large ships satisfy IMO's standards, pilots may feel difficult in passing through in curved, narrow waterway.

Acknowledgements

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