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A Study on Yaw-checking and Course-keeping Ability of Directionally Unstable Ships

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Abstract : *Yaw-checking and course-keeping ability in IMO's ship manoeuvrability standards are 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 six operators(five active pilots and one ex-captain) 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 revised criteria are proposed.*

Key words : *IMO's ship manoeuvrability standards, Yaw-checking, Course-keeping, Simulator experiment, Manoeuvring difficulty*

1. Introduction

Recent marine disaster of large ships often causes serious oil pollution. To prevent or reduce such a disaster, International Maritime Organization (IMO) has been endeavoring to improve ship's manoeuvrability, and adopted the standards A751(18) in 1993(Kang, 1993) and MSC 137(76) in 2002(IMO, 2002). 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 on the criteria for the yaw-checking and course-keeping ability. Firstly, the authors take three kinds of ship built in Korea recently, from which they prepare the virtual 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 (directional unstability) and degree of manoeuvring difficulty felt by pilots. Finally, the IMO's standards are discussed, and revised 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. The authors prepare three models of series-ships with different, systematic unstability.

Table 1 Principal dimensions of actual-ships

Ship	A	B	C
Kind of ship	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	0.839
Design speed V (kt)	15.0	23.5	13.5
L/V (sec)	12.0	22.7	43.2

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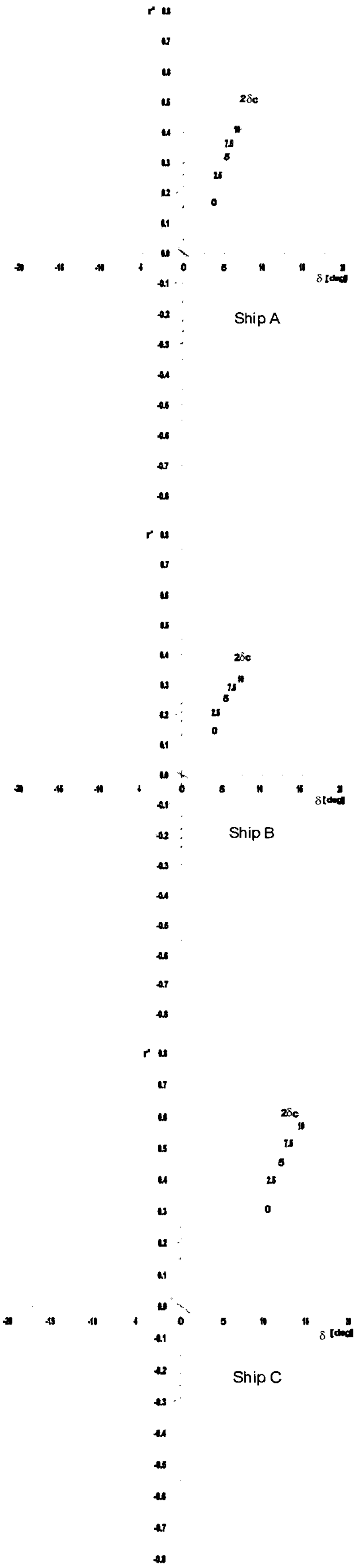

Fig. 1 Spiral curves of series-ships with different spiral loop width

In this paper, four linear hull derivatives will change gradually their values for consideration of stern frame line, such as U or V shape of stern body. In order to realize this, the authors refer to the experimental result on the effect of stern frame shape on linear derivatives, which was carried out in SR221 project(Yoshimura, 1995). And simultaneously rudder area ratios will also change gradually their values for consideration of profile effect at stern. The other coefficients and non-linear hull derivatives will not change their values. The mathematical model for simulation will be mentioned in following section. Fig. 1 shows the 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.

2.2 Mathematical model for simulation

In this paper, the modular-type mathematical model is employed for prediction of manoeuvrability in numerical simulation and in simulator experiment as well. The mathematical model is summarized as follows. Following the sign convention of Fig. 2, the basic equation of manoeuvring motion can be written as :

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

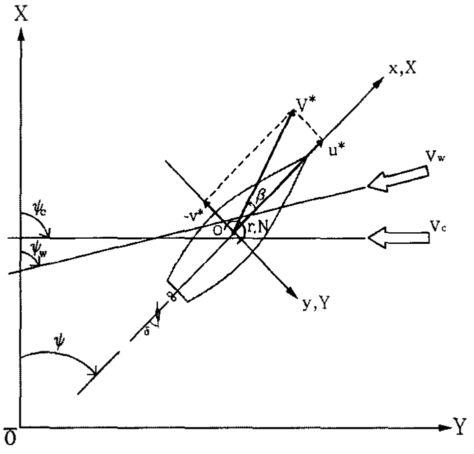

Fig. 2 Co-ordinate system and definition of symbols

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, 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. The dot over parameters of ship motion denotes time derivative. If the added mass and added moment of inertia are taken into account and modular-type model, such as MMG model, is employed, Eq. (1) will be expressed as follows :

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

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 to take the current forces into account, 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 over ground, Ψ yaw angle, V_c current velocity, and Ψ_c current direction(Fig. 2). Eqs. (2) and (3) give the following.

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

One of the authors(Sohn, 1992) proposed a mathematical model of hull damping forces at low advance speed with large drift angles as Eq. (5). The model originated from Takashina's experimental study(Takashina, 1986) and was modified in view of practical use. Comparing Eq. (5) with (Takashina, 1986), only three non-liner terms, namely Y_{vvvvv}', N_{vvv}', and N_{uvvv}' are omitted in Eq. (5) :

$$\begin{aligned}
X_H &= 0.5\rho LdV^2\{X_{uu}'u'|u'|+X_{vr}'v'r'\}\\
Y_H &= 0.5\rho LdV^2\{Y_v'v'+Y_{ur}'u'r'\\
&\qquad +Y_{vv}'v'|v'|+Y_{vr}'v'|r'|+Y_{urr}'u'r'|r'|\}\\
N_H &= 0.5\rho L^2dV^2\{N_v'v'+N_{uv}'u'v'+N_r'r'\\
&\qquad +N_{vvr}v'^2r'+N_{uvrr}u'v'r'^2+N_{rr}'r'|r'|\}
\end{aligned} \tag{5}$$

where ρ denotes density of sea 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-dimensionalized as follows.

$$\begin{aligned}
&V=\sqrt{u^2+v^2},\ u'=u/V\\
&v'=v/V,\ r'=r\cdot L/V\\
&X_H'=X_H/0.5\rho LdV^2\\
&Y_H'=Y_H/0.5\rho LdV^2\\
&N_H'=N_H/0.5\rho L^2dV^2
\end{aligned} \tag{6}$$

In this model, the low advance speed effect is reflected on some of terms in which u' is added, and minus sign of u' means backing motion. In case of normal advance speed, which is relatively high advance speed, the value of u' becomes almost 1.0, then Eq. (5) exactly coincides with (Inoue, 1981 ; Hirano, 1992 ; Mikelis, 1985) also suggested the same mathematical model as Eq. (5) for practical prediction of manoeuvring motion at low advance speed.

Propeller and rudder forces must be expressed in four quadrants of propeller operation. The detailed expression of X_P, Y_P, N_P, X_R, Y_R, N_R is referred to Reference(Sohn, 1997), which was published previously by one of the authors. In this paper, the authors summarize briefly the mathematical model of propeller and rudder forces applied to first quadrant region only as follows :

$$\begin{aligned}
X_P &= (1-t)K_T\rho n^2D^4\\
X_R &= -(1-t_R)F_N\sin\delta\\
Y_R &= -(1+a_H)F_N\cos\delta\\
N_R &= -(x_R+a_Hx_H)F_N\cos\delta
\end{aligned} \tag{7}$$

where n denotes number of propeller revolutions per second, K_T thrust coefficient, D propeller diameter, t thrust deduction factor, x_R x-coordinates of rudder, δ rudder angle, and t_R, a_H and x_H interactive coefficients. F_N represents rudder normal force and is expressed as follows :

$$
\begin{aligned}
F_N &= \frac{1}{2}\rho A_R V_R^2 f_a \sin\alpha_R \\
V_R &= \sqrt{u_R^2 + v_R^2} \\
\alpha_R &= \delta - \tan^{-1}(v_R / u_R) \qquad (8) \\
u_R &= \varepsilon n P \sqrt{1 - 2(1-\eta k)s + \{1 - \eta k(2-k)\}s^2} \\
v_R &= -\gamma_R(v + l_R r)
\end{aligned}
$$

where A_R denotes lateral projected rudder area, V_R effective in-flow velocity past rudder, f_a gradient of rudder normal force to attack angle, and γ_R flow straightening coefficient. The other symbols appeared in Eq. (8) are referred to (Yoshimura, 1978).

Hydrodynamic derivatives and many other coefficients appearing in mathematical model can be obtained from a variety of References(Inoue, 1981) (Van, 1969) (Fujino, 1978). Wind forces, namely X_W, Y_W and N_W are estimated by (Isherwood, 1973).

2.3 Simulated overshoot angle of Z-test

Fig. 3, 4 and 5 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 result tells us that the spiral loop width has strong correlation with the 1st overshoot angle of 10 deg Z-test. The 2nd overshoot angle of 10 deg Z-test is about 2 or 2.5 times larger than the 1st one of 10 deg Z-test, and the 1st overshoot angle of 20 deg Z-test is about 5 or 10 degrees larger than the 1st one of 10 deg 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. The correlation lines between abscissa and ordinate in Figs. 4 and 5 illustrate the same equation as mean line arranged from sea trial database by (Yoshimura, 2000).

3. Simulator experiment

The authors carried out simulator experiment in order to grasp the correlation between overshoot angles provided in IMO's standards and the degree of manoeuvring difficulty felt by operators. The shiphandling simulator has been constructed by the authors for this objective. The schematic of system configuration for the present simulator is shown in Fig. 6. Table 2 shows an outline of present simulator.

The situation of passing ship in a curved, narrow waterway is taken as simulation scenario. The authors select the east waterway of designated area of Inchon Harbour Approaches. Fig. 7 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°) and current as 2 kt to NE(050°). One of the mission to shiphandling is passing along the waterway centerline as close as possible and the other is keeping propeller revolution constant as that of harbour full speed.

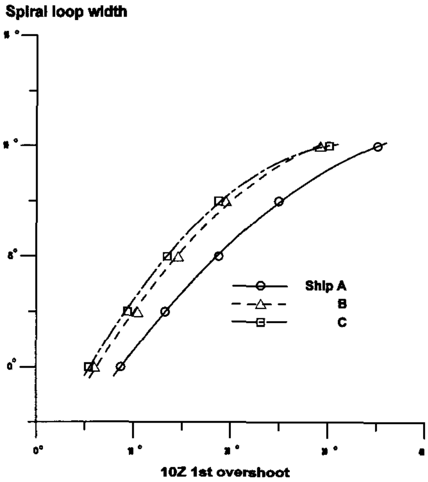

Fig. 3 Relation between spiral loop width and the 1st overshoot angle of 10 deg Z-test by numerical simulation

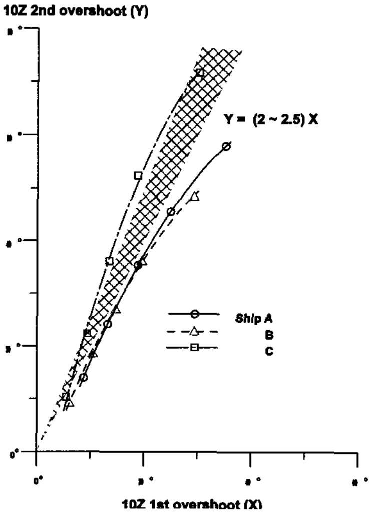

Fig. 4 Relation between the 1st and the 2nd overshoot angles of 10 deg Z-test by numerical simulation

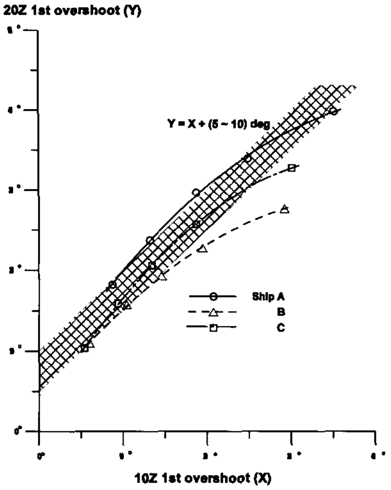

Fig. 5 Relation between the 1st overshoot angle of 10deg Z-test and the 1st overshoot angle of 20deg Z-test by numerical simulation

Those are 12 kt in training ship, 17.6 kt in container ship and 10.8 kt in bulk carrier respectively. Only rudder command is allowed and operator issues the order to helmsman orally. Six ship operators participate in the simulator experiment. Five operators are pilots on service in Korea, who have pilotage experience of one to five years after serving on merchant ships for about 10 years or more. And remaining one operator is one of the authors, who has captain experience of 3 years. Before the simulator experiment, brief explanation is given to operators on the objectives 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. Fig. 8 shows root-mean-square value (RMS) of ship's lateral deviations from waterway centerline during simulation. We can see that lateral deviation has little correlation with spiral loop width. Fig. 9 shows root-mean-square value of rudder angles applied during simulation. Applied rudder angle has correlation with spiral loop width, even though some differences in magnitude are appeared according to model of series-ships, namely the ratio of ship length to design speed (L/V). Fig. 10 shows the degree of manoeuvring difficulty in terms of rating scale evaluated subjectively by operators. The evaluation has 10 rating scales from 0 to 9. Larger rating scale means more difficulty of manoeuvring. The rating scale is evaluated by operators immediately after every execution of simulation. The subjective evaluation rating scale has strong correlation with spiral loop width.

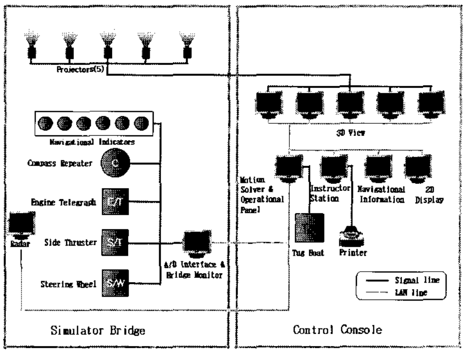

Fig. 6 Schematic of system configuration for present simulator

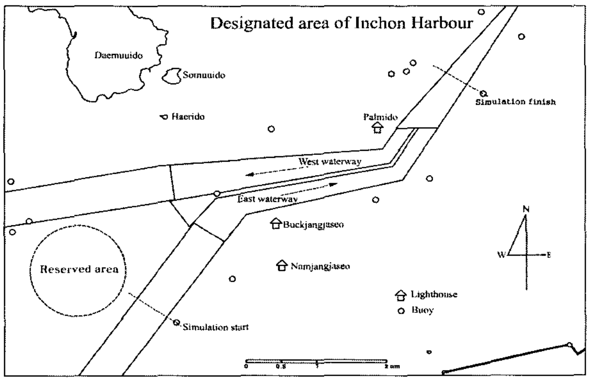

Fig. 7 Map of waterway and Inchon Harbour Approache employed for present simulator study

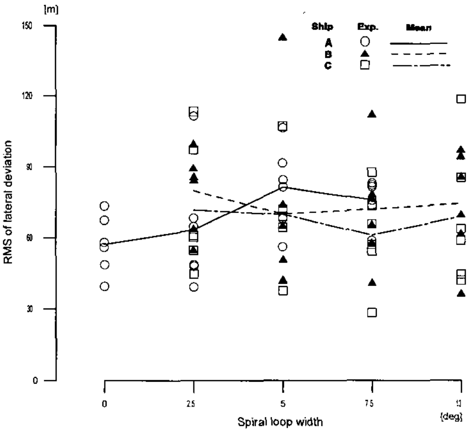

Fig. 8 Root-mean-square value of lateral deviations from waterway centerline during simulation

Table 2 Outline of present simulator

Bridge dimension	W 5.1m * D 3.5m * H 2.3m
Display system	Front projection system LCD Projector : 5 channels (Max. 3200 ANSI lumens) Flat screen(120") : 5 channels
Field of view	Horizontal : 175 degrees Vertical : 26.3 degrees
Image generation system	Hardware : Pentium 4, 2.0 GHz Software : Vega NT (Multigen-Paradigm Co.) Frame rate : 30 frame/sec

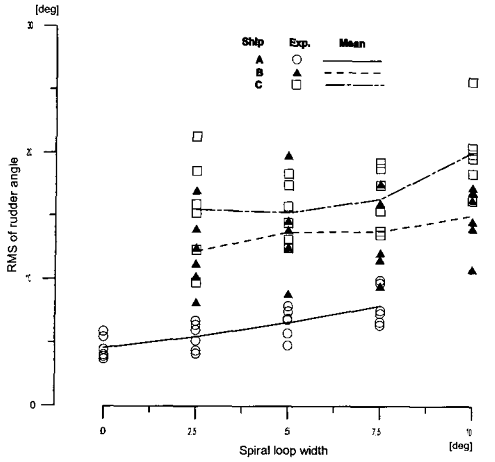

Fig. 9 Root-mean-square value of rudder angles applied during simulation

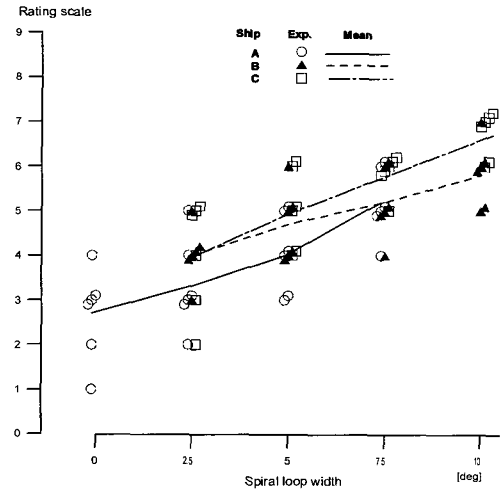

Fig. 10 Subjective rating scales evaluated by operators just after simulation

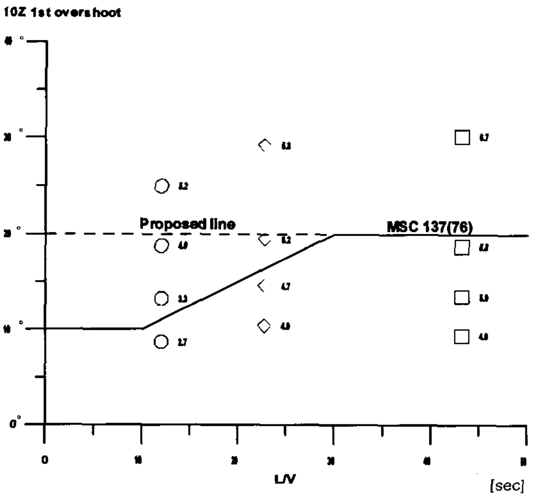

Fig. 11 Mean values of subjective rating scales displayed on IMO's standard diagram (the 1st overshoot angle of 10 deg Z-test)

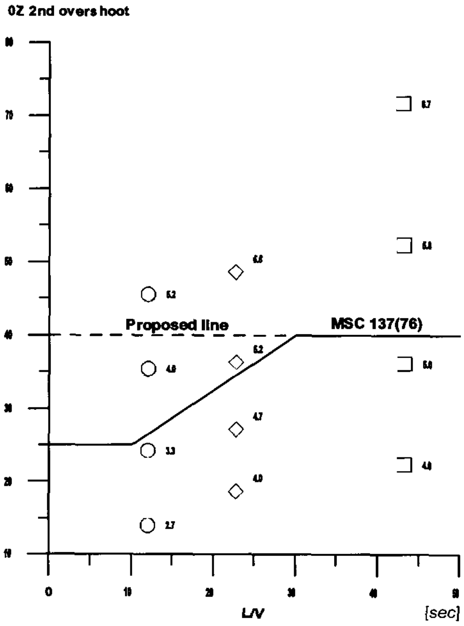

Fig. 12 Mean value of subjective rating scales displayed on IMO's standard diagram (the 2nd overshoot angle of 10 deg Z-test)

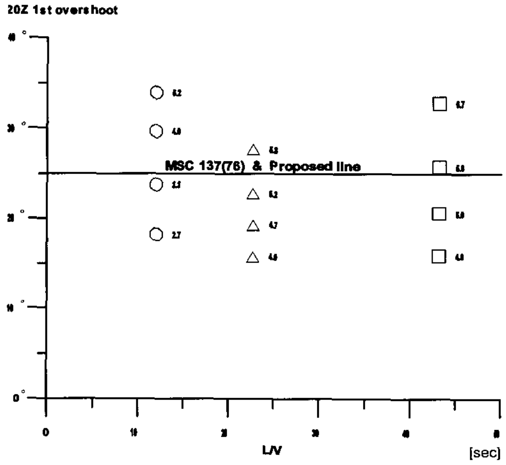

Fig. 13 Mean value of subjective rating scales displayed on IMO's standard diagram (the 1st overshoot angle of 20 deg Z-test)

Figs. 11, 12 and 13 show IMO MSC 137(76) criterion diagram(IMO, 2002), on which the overshoot angle and the mean value of rating scale according to spiral loop width of three models of series-ships have been marked and displayed. In Fig. 11, the IMO criterion MSC 137(76) requires the different values of overshoot angle along L/V parameter in order to take the response of steering gear into consideration. However the simulator experiment tells us that the manoeuvring difficulty rather decreases as L/V decreases, in case the overshoot angle is nearly the same.

So the authors propose 20 degrees as the limit line of the st overshoot angle of 10 deg Z-test regardless of L/V alues, which means almost 5 in rating scale. In Fig. 12, he authors propose 40 degrees as the limit line of the 2nd vershoot angle of 10 deg Z-test regardless of L/V values, hich has been decided in consideration of rating scale 5 in anoeuvring difficulty and also numerical simulation result n the relation between the 1st and the 2nd overshoot ngles in 10 deg Z-test (Fig. 4). In Fig. 13, the authors ropose the same values as that of IMO MSC 137(76) in onsideration of rating scale 5 in manoeuvring difficulty and lso numerical simulation result on the relation between the 1st overshoot angle of 10 deg Z-test and the 1st one of 20 eg Z-test (Fig. 5). In addition, it is found from Figs. 11, 12 nd 13 that even though spiral loop widths are the same mong three models of series-ships, the fairway passing of hips with large L/V, on the whole, is more difficult than hat of ships with small L/V.

4. Conclusions

Through the simulator study using three models of eries-ships with the different spiral loop width, the authors ave reviewed IMO's ship manoeuvrability standards articularly focusing on the criterion for yaw-checking and ourse-keeping ability. As far as the present simulator tudy is concerned, the major concluding remarks are ointed 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. Revised criteria on yaw-checking and course-keeping ability are proposed in view of degree of manoeuvring difficulty.
4. Even though the spiral loop widths are the same among three models of series-ships, the fairway passing of ships with large L/V, on the whole, is more difficult than that of ships with small L/V.

Acknowledgements

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