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A Study on Construction of Collision Reproducing Simulator and Application to Analysis of Marine Casualty

Kyoung-ho Sohn · Jun-young Bae***

**Dept. of Ocean Systems Engineering, Korea Maritime University, Busan 606-791, Korea*
***Graduate School, Korea Maritime University, Busan 606 791, Korea*

Abstract : *Ships' collision accident has often occurred in congested waterways or in harbour areas. To examine the cause of collision accident may be necessary to prevention against another similar one. We discuss the construction of ship-manoeuvring-simulator system used for reproducing ships' collision phenomenon. The system consists of one simulator bridge for own ship and two control consoles for own ship and target ship. Own ship and target ship are linked each other, and are simultaneously manoeuvred in simulator bridge or at control console respectively. And a simulator experiment for reproducing ships' collision phenomenon and for examining the cause of accident is carried out. Through the present case study, we find out that the constructed simulator system is very useful for reproducing ships' collision phenomenon and for examining the cause of accident.*

Key words : *Ships' collision accident, Ship-manoeuvring-simulator, Manoeuvring motion*

1. Introduction

Recently there is a growing tendency that some ships have become larger, faster and more specialized than ever before. So the environment of ship operation has grown worse and collision risk will be higher especially in congested waterways or in nearby harbour areas. Collision accident of large ships often leads to serious oil pollution on the sea. To examine the cause of collision accident may be necessary to prevention against another similar new one.

In this paper, we discuss construction of ship manoeuvring simulator system used for reproducing collision phenomenon and for examining the cause of collision accident. And a simulator experiment, based on real collision accident, has been carried out as a case study and cause of accident has been examined.

2. System configuration of ship manoeuvring simulator and 3 dimensional image modeling

2.1 System configuration of ship manoeuvring simulator

Fig. 1 shows schematic of system configuration of present simulator. The simulator bridge consists of a number of navigational instruments and display modes such as steering wheel, side thruster, engine telegraph transmitter, compass repeater, navigational indicators, radar and projection system for outside view. The control console consists of two parts. One is for own ship and the other for target ship. The own ship can be manoeuvred in simulator bridge or at control console, whereas the target ship can be done only at control console. We adopt the distributed data processing network system, namely UDP(User Datagram Protocol) or TCP(Transmission Control Protocol) with asynchronous sockets, for data transmission among all the computers used in the simulator[1]. Fig. 2 shows photographs of simulator bridge and control console. Table 1 shows the specification of present simulator.

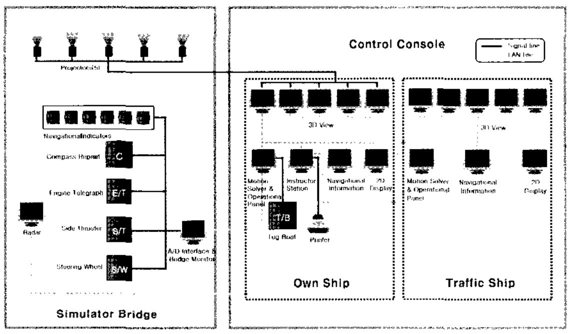
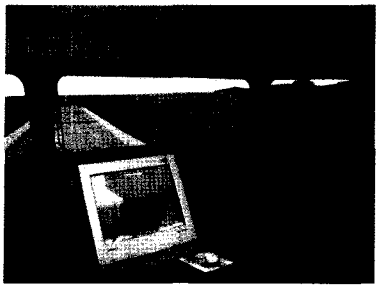


Fig. 1 Schematic of system configuration

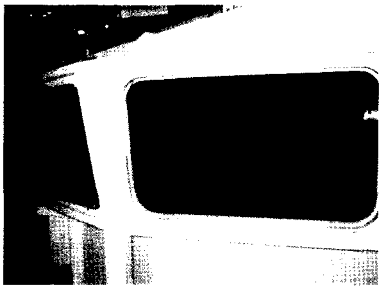
Table 1 Specification of present simulator

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 Inc.) Frame rate : 30 frame/sec

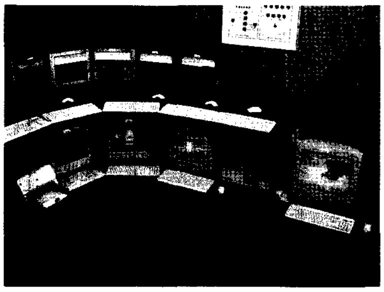
* Corresponding Author : Kyoungho Sohn, sohnkh@kmaritime.ac.kr 051)410-4303
** newthousands@bada.hhu.ac.kr 051)410-4991



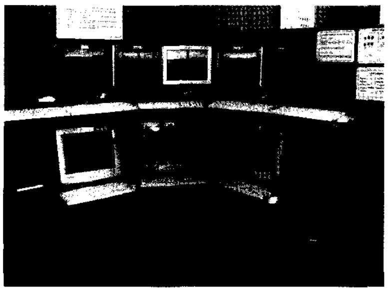
(a) Inside of simulator bridge



(b) Outside of simulator bridge



(c) Control console for own ship



(d) Control console for target ship

Fig. 2 Photographs of simulator bride and control console

2.2 3 dimensional image modeling

It is necessary to generate 3 dimensional image database for a large number of objects such as geographical features, ships and the others so as to make VR(Virtual Reality) simulation possible. As 3 dimensional modeling tool for this purpose we use MultiGen Creator(MultiGen-Paradigm Inc.), which is based on OpenFlight scene description database[2]. Next we need 3 dimensional rendering technique for real time animation. For this application, we use graphic display software Vega NT(MultiGen-Paradigm Inc.), which is based on OpenGL VR simulation. On the basis of OpenFlight file format(FLT file) of object models created by MultiGen, VRimage file, which is denoted as Application Definition File(ADF file), can be generated by Vega NT. And ADF file is linked with Visual C++ programming for ship manoeuvring motion or for some others necessary.

3. Mathematical model for ship manoeuvring motion

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. 3, the basic equation of manoeuvring motion can be written as :

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

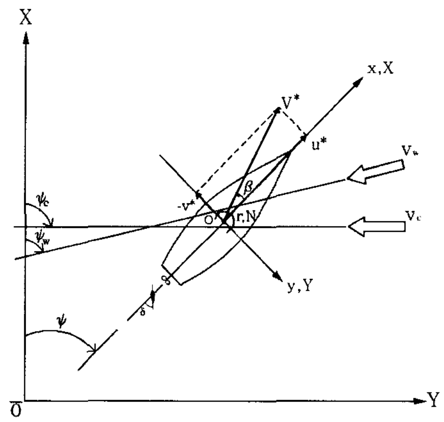


Fig. 3 Co-ordinate system and definition of symbols

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 force 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(cf. Fig. 3). Eqs. (2) and (3) give the following.

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

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(1986) and was modified in view of practical use. Comparing Eq. (5) with Takashina model (1986), only three non-liner terms, namely Y_{vvvvv}', N_{vvv}' and N_{uvvv}' are omitted in Eq. (5) :

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

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.

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

In this model, the low advance speed effect is reflected on some 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 Eq. (5) exactly coincides with Inoue model(1981). Hirano(1992) 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 can be found in sohn, et al.(1997). In this paper, we 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 submerged 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 et al(1987) Van Lammeren et al(1969) and Fujino et al(1978).

Hydrodynamic derivatives and many other coefficients appearing in mathematical model can be obtained from a variety of Inoue et al(1981). Wind forces(X_W, Y_W and N_W), which are functions of wind velocity and wind direction(cf. V_W and Ψ_W in Fig. 3), are estimated by Isherwood(1973). The mathematical model for ship with twin screws and twin rudders is referred to Sohn et al(2001).

4. Application to collision accident

Using the constructed simulator, we reproduce a collision phenomenon, which was actually occurred between Ship A and Ship B in Pohang-harbour, and we examine the cause of collision accident. The outline of the accident is as follows. Ship A was approaching to Pohang-harbour for mooring at M7 anchorage, whereas Ship B was leaving the port at almost same time. The collision accident was occurred on 02:06:30, 22nd April, 2002. Ship B struck Ship A on starboard side of fore body and a few minutes later Ship A sank.

4.1 3 dimensional image generation of ships and harbour

We prepare 3 dimensional ship models and manoeuvring performance of Ship A and Ship B respectively according to above mentioned method, and also prepare 3 dimensional geographical model of Pohang-harbour and surrounding area, referring to the followings.

(1) Preparing for model of Ship A
- Principal dimensions of Ship A
- General arrangement of Ship A
- Photographs of a certain cargo ship similar to Ship A

(2) Preparing for model of Ship B
- Principal dimensions of Ship B(barge-pusher combination system)
- General arrangement of Ship B
- Manoeuvring sea trial data of Ship B
- Photographs of Ship B

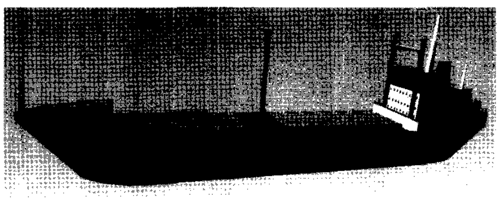
(3) Preparing for geographical model of Pohnag harbour and surrounding area
- Numerical chart of Pohang-harbour
- Paper chart of Pohang-harbour

Table 2 Principal dimensions of subjected ships

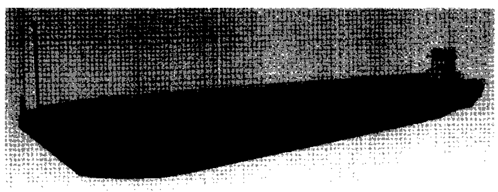
			Ship A	Ship B		
				Barge	Pusher	Barge/Pusher
Hull						
Length over all	L_{OA}	(m)	93.93	139.0	32.0	152.0
Length bet. per.	L	(m)	82.0	137.0	30.0	145.0
Breadth	B	(m)	14.4	19.5	13.0	19.5
Depth	D	(m)	7.10	8.85	6.52	
Draft	d	(m)	5.9	4.5	4.5	4.5
Block coef.	C_B		0.76	0.8	0.75	about 0.8
Rudder						
Area	A_R	(m^2)	8.849		7.26*2	
Height	H	(m)	3.59		3.3	
Aspect ratio	,		1.456		1.5	
Area ratio	A_R/Ld		1/55.6			
Propeller						
Diameter	D	(m)	3.3		2.6*2	
Pitch	P	(m)	2.64		2.1	
Pitch Ratio	P/D		0.8		0.8	
Expanded area ratio			0.62		0.62	
Number of Blades			4		4	

*2 means twin propellers or twin rudders.

Table 2 shows the principal dimensions of Ship A and Ship B(barge, pusher and barge-pusher combination system). Fig. 4 shows 3 dimensional model of both ships. Fig. 5 shows the 3 dimensional model of Pohang-harbour and surrounding area.



(a) Ship A



(b) Ship B

Fig. 4 3 dimensional modeling of subjected ships

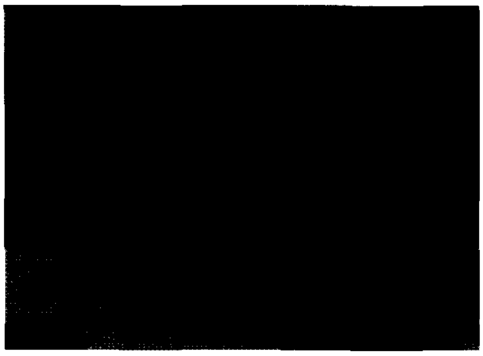


Fig. 5 3 dimensional modeling of Pohang-harbour and surrounding area

4.2 Simulator experiment

4.2.1 reproducing collision phenomenon and examining the cause of collision

Fig. 6 shows real trajectories and positions of both ships for about 10 minutes just before collision accident. The positions are shown together with real time and numeral letters from ⑪ to ⑳, which were written for convenience. Fig. 6 was prepared by computer image data which were provided by Port Traffic Management Service Center, Pohang Regional Maritime Affairs and Fisheries Office(Port Traffic Management Service Center, 2002).

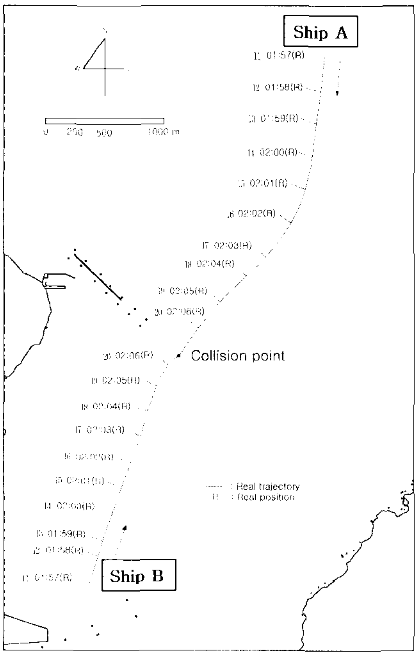


Fig. 6 Real trajectories and positions of both ships for about 10 minutes just before collision accident

We carried out simulator experiment on reproducing collision phenomenon and attempted to examine the cause of accident. Simulation was started at the position of ⑮, which corresponded to 02:01. Initial speed of Ship A was set to 10.5 kt, and that of Ship B to 7.2 kt. Both ships are manoeuvred by only rudder deflection so as to coincide with real trajectories as far as possible. Any other ship besides Ship A and Ship B did not exist around them. External forces due to wind or current were not considered in this experiment. The real collision accident was occurred at night time and the visibility at that time was so good to become about 5 to 6 miles. But in the simulator experiment, we assumed daytime environment so as to ensure the above mentioned visibility. Fig. 7 shows the result of simulator experiment.

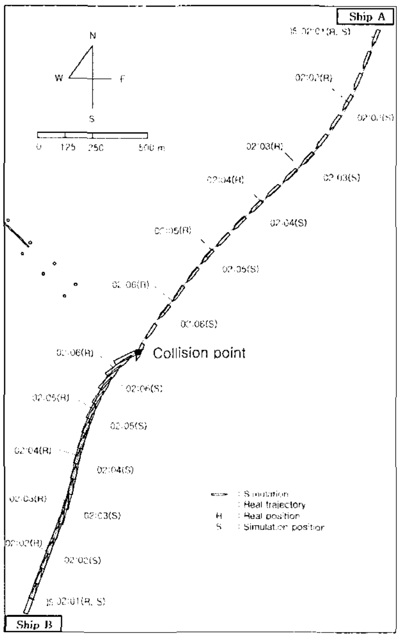


Fig. 7 Comparison of trajectories and positions of both ships by simulator experiment on reproducing collision accident with real ones

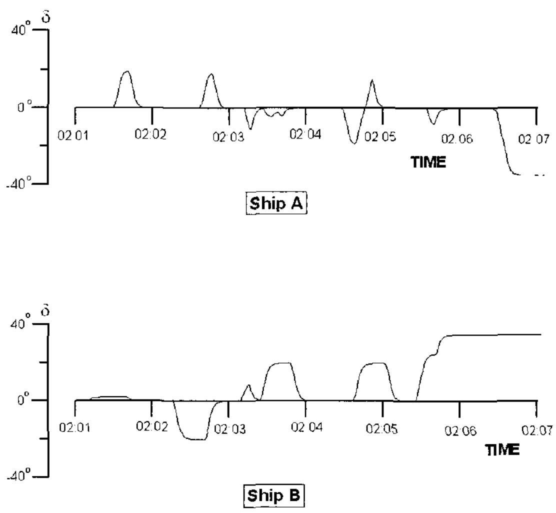


Fig. 8 Changes in rudder angles during simulator experiment on reproducing collision accident

We compared trajectories and positions by simulation with real ones in the accident. From Fig. 7 we can see that trajectories and positions of both ships, collided point, collision angle between both ships, and etc. by present simulation well coincided with real ones in the accident. Fig. 8 shows changes in rudder angles of both ships during simulator experiment on reproducing collision phenomenon. From Fig. 8 we can see that Ship B executed deflection of starboard rudder at about 02:05:30 and one minute later Ship A executed deflection of port rudder, which led to collision each other. So we can say the cause of accident as follows.

- At the position of ⑯ or ⑰, which corresponded to 02:02 or 02:03, Ship B was situated as 'Give-way vessel' and Ship A as 'Stand-on vessel'. At this situation, the delay of start to avoiding action by Ship B might provide one of causes of accident.
- After execution of rudder deflection to starboard by Ship B as an avoiding action, Ship A altered course to port instead of doing to starboard, which might be the decisive cause of accident. It should be noted that Ship A should have not altered course to port but to starboard for Ship B on her own port side.

4.2.2 Some other simulation for examining the cause of collision

When two ships are approaching each other so as to involve risk of collision, it is very important to decide the time to apply sailing rule between both ships. Here we thought two scenarios of the time to apply sailing rule as follows.

(1) In case that sailing rule on crossing situation was applied from about 10 minutes before collision

At the position of ⑪, which corresponds to 01:57 and is deemed to be that both ships could take early and substantial action to keep well clear each other, both ships were situated as follows:

- Course of Ship A 180°
- Course of Ship B 023°
- Angle of intersection between both ships 23°
- Distance between both ships 2.64 sea-miles

At the above circumstances both ships were deemed to be in crossing. Ship A was situated as 'Give-way vessel' and Ship B as 'Stand-on vessel'. The scenario of simulator experiment was that both ships started at the position of ⑪, and initial speed of Ship A was set to 10.5 kt and that of Ship B to 7.2 kt, and from this position both ships were manoeuvred so as to keep the initial courses, which corresponded to the courses at the position of ⑪. The result of experiment is shown in Fig. 9. We can see that both ships could keep well clear each other. If Ship A took early and substantial action as 'Give-way vessel', the collision could be avoided. So Ship A should be responsible for the collision accident as far as this sailing rule is applied.

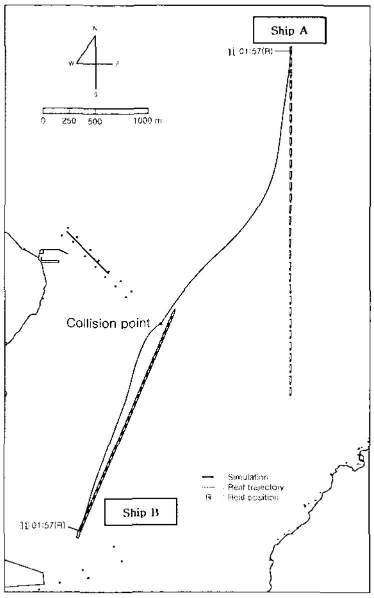


Fig. 9 Simulator experiment based on scenario (1)

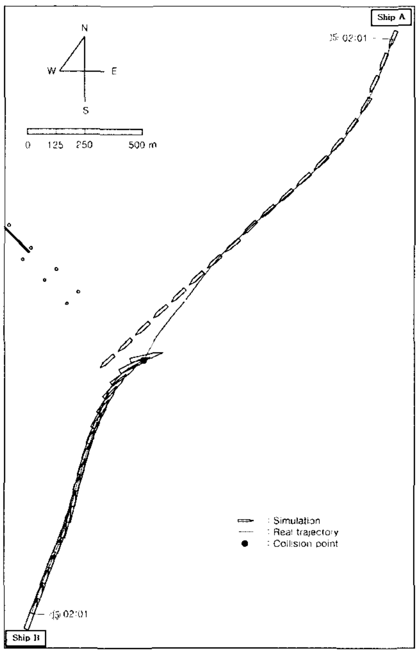


Fig. 10 Smulator experiment based on scenario (2)

(2) In case that sailing rule on crossing situation was applied from about 4 minutes before collision

Simulation was started at the position of ⑮, which corresponded to 02:01. Initial speed of Ship A was set to 10.5 kt and that of Ship B to 7.2 kt. Both ships were manoeuvred so as to coincide with real trajectories as close as possible by 02:03, which corresponded to the position of ⑰. From then Ship B was manoeuvred so as to coincide with real trajectories as close as possible, whereas Ship A was manoeuvred so as to keep the same course as that at 02:03. At the position of ⑰, distance between both ships was about 1.3 sea-miles and Ship A was situated as 'Stand-on vessel' and Ship B as 'Give-way vessel'. The result of the simulator experiment is shown in Fig. 10. From Fig. 10 we can see that if Ship A kept her course as 'Stand-on vessel', the collision risk were avoided. In this experiment, DCPA(Distance of Closest Point of Approach) measured about 100 m, which barely escaped collision. So Ship A should be responsible for the collision accident as far as this sailing rule is applied.

5. Conclusion

Through the above mentioned study, the followings can be drawn.

1. The constructed ship-manoeuvring-simulator is very useful for reproducing collision phenomenon and for examining the cause of accident.
2. By using the constructed simulator, we can analyze various physical factors related to the collision accident.
3. As a case study, we could reproduce collision phenomenon and could examine effectively the cause of collision accident, which was actually occurred between Ship A and Ship B in Pohang harbour on 22nd April, 2002.

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