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Experimental Study on Automatic Control for Collision Avoidance of Ships

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Abstract

Automatic control system is widely applied to control the ship direction or heading angle in accordance with the decided trajectory. Several methods for improving performance of control system have been developed such as Proportional-Integral-Derivative (PID) control and fuzzy logic based control. Within the last decade, application of automatic control system is not only for ship navigation but also for avoiding collision risk of ships in seaways. This paper discusses the application of automatic control system for avoiding ship collision by free running experiment. Fuzzy logic based control was developed using Mamdani Centroid method to estimate the necessary rudder angle in order to change the ship heading angle. Collision scenario was designed using four fixed obstacles with a certain distance which will be avoided by ship model. The results of free running experiment showed that the automatic control system can minimize the risk against collision or at least provide initial warning that may be faced by the ship. with minimum distance of 3.50 of length between perpendicular. To improve performance of control, external disturbance such as wind and wave should be considered in the design of automatic control system.

Abstract

Studi Eksperimental Kendali Otomatis untuk Pencegahan Tabrakan pada Kapal Laut. Sistem kendali otomatis telah banyak diaplikasikan untuk mengendalikan arah gerak atau sudut haluan kapal sesuai dengan jalur lintasan yang telah ditentukan. Beberapa metode untuk memperbaiki unjuk kerja sistem kendali otomatis telah dikembangkan seperti kendali *Proportional-Integral-Derivative* (PID) dan kendali berbasis logika *fuzzy*. Dalam satu dekade terakhir, aplikasi sistem kendali otomatis tidak terbatas hanya untuk peralatan navigasi tetapi telah dikembangkan untuk membantu dalam menghindari kemungkinan terjadinya tabrakan kapal selama pelayaran. Penelitian ini membahas tentang aplikasi sistem kendali otomatis untuk pencegahan tabrakan kapal dengan pengujian model. Sistem kendali berbasis logika *fuzzy* digunakan untuk mengontrol sudut kemudi sesuai dengan sudut *heading* atau arah gerak kapal yang diinginkan dengan menggunakan metode *Mamdani Centroid*. Skenario tabrakan dalam pengujian model didesain dengan menggunakan 4 penghalang yang harus dihindari oleh kapal. Hasil pengujian model menunjukkan bahwa sistem kendali dapat memperkecil resiko tabrakan kapal atau minimal dapat memberikan peringatan dini akan potensi tabrakan yang mungkin dihadapi oleh kapal. Untuk memperbaiki kinerja sistem kendali, gangguan dari luar seperti angin dan gelombang harus dipertimbangkan dalam perancangan sistem kendali otomatis kapal.

Keywords: automatic control, collision, manoeuvring

1. Introduction

The International Maritime Organization (IMO) published regulation for collision avoidance in order to minimize collision risk of a ship in seaways [1]. Nevertheless, some collision still occured either between two ships or between ship with another floating object. Several results of investigation reported that retardation response of shipmaster, loss function of navigation equipments, failure ofrudder system or weather are the main cause of collision occurrence. Therefore, several researches for collision avoidance had been conducted to develope methology or technique to minimize the collision risk of a ship in seaways. Since IMO introduced the automatic identification system (AIS) as one of the navigation equipment for seagoing ships, the automatic control system becomes an interesting research topic mainly for reducing collision risk in seaways. Perera, *et al.* [2] proposed guidance and autonomous navigation based on collision regulation of IMO using fuzzy logic based control. Tsou, *et al.* [3] developed an automatic control system using AIS in order to identify obstacles or other ships near the controlled ship in order to avoid ship collision. Tam, *et al.* [4] designed an automatic control system for collision avoidance based on decided ship's trajectory with some other ships around the controlled ship. A similar research was conducted by Shih, *et al.* [5] in order to show that the automatic control system can be effectively used to minimize collision risk or at least to provide early warning system to the ship master regarding the collision dangerous. Fahmi [6] designed an automatic control system by means fuzzy logic method in order to avoid collision of an Indonesian roro ferry in seaways. His work was conducted by numerical simulation using three degree of freedom mathematical model with mathematical modelling group (MMG). As the forces and moments act on ship hull are separately calculated [7], application of automatic control system on MMG model can be easily developed. Application of automatic control in MMG model based on AIS data has been developed for prediction of collision risk of ship [8]. The formula for estimating each component of forces and moments act on ship hull has been developed by some authors [9,10]. Therefore the MMG model becomes more applicable in practical point of view.

Performance of the automatic control depends on maneuvering characteristics and external disturbance acting on ship hull as shown by Shih, *et al*. [5]. This means that the control system should be designed based on hydrodynamic characteristics of ship hull, external disturbances following the mathematical model of ship maneuvering. Therefore, the maneuvering characteristics including the hydrodynamic forces and moments acting on ship hull should be accurately estimated in order to obtain an accurate control system. The control system is meant to change the rudder angle following the necessary heading angle in order to avoid collision dangerous. In cases of the obstacle have been very close to the controlled ship, the control system can provide early warning to the ship master for taking necessary action.

Other than the numerical simulation have been conducted by several authors, a free running model experiment is necessary in order to validate the accuracy of proposed numerical simulation model. The main difficulty of model experiment for collision avoidance with automatic control system is modelling the collision scenario. More than one model should be controlled at the same time with variation of motion characteristics during experiment. Fixed object assumption for target ship or other obstacles in seaway may become an alternative solution for conducting model experiment of collision avoidance. This idea seems to be appropriate method because per-formance of the control system as well as the minimum distance for the control to take action can be evaluated in detail. This paper discusses about application of automatic control system to minimize collision risk of a ship in seaways by free running model experiment. This experiment is conducted in order to validate performance of a designed control system [6]. The maneuvering parameters to be validated consist of ship trajectory, rudder angle, heading angle and ship velocity. Here, the effects of external disturbances during the experiment were not taken into account.

2. Methods

Subject Ship. An Indonesian ro-ro ferry was used as sample ship for the free running experiment. This ship has been used in several researches regarding manoeuvring performance [11,12], therefore some data dealing with manoeuvring may easily be obtained. The ship has smalldraught with large breadth. This is the main characteristic of Indonesian ro-ro ferries especially the ships built in Indonesian shipyard. Those geometries may have sig-nificant effect on its manoeuvring characteristic. The principle dimension as well as the propeller and the rudder geometries of subject ship are shown in Table 1 and Table 2, respectively. The model scale used for the experiment was 1:25. The ship model including equipment and instrument for conducting the free running experiment are shown in Figure 1.

In the numerical simulation, the hydrodynamics coefficient of ship hull were estimated by using formula proposed by Yoshimura and Masumoto [9]. Here, effect of interaction between rudders as well as the interaction between propellers were neglected. Actually, the propeller thrust as well as the rudder forces and moment of ship with single propeller and single rudder is different with a ship with twin propeller and twin rudder due to the interaction between propellers and between rudders during operation [13]. This interaction effect tended to decrease as the distance between propellers and the dist-

Table 1. Principles Dimension of Subject Ship

Length overall(L_{OA})	36.40 m
Length between perpendicular(L_{BP})	31.50 m
Breadth(B)	8.70 m
Height(H)	2.65 m
Draught(T)	1.65 m
Ship speed(V_S)	10.5 knot
Block coefficient(C_B)	0.63
Midship coefficient(C_M)	0.986
Waterline coefficient(C_W)	0.886
Prismatic coefficient(C_P)	0.804

Table 2. Propeller and Rudder Geometries

Number of propeller	2
Propeller blade (Z)	4
Propeller diameter (D_P)	1.10 m
Propeller revolution (n)	8.58 rps
Transverse position propeller (y_P)	±2.55 m
Long. position propeller (x_P)	15.50 m
Rudder area (A_R)	2.08 m^2
Rudder coefficient (f_A)	2.10
Transverse rudder position (y_R)	±2.55 m
Long. Rudder position (x_R)	15.75 m

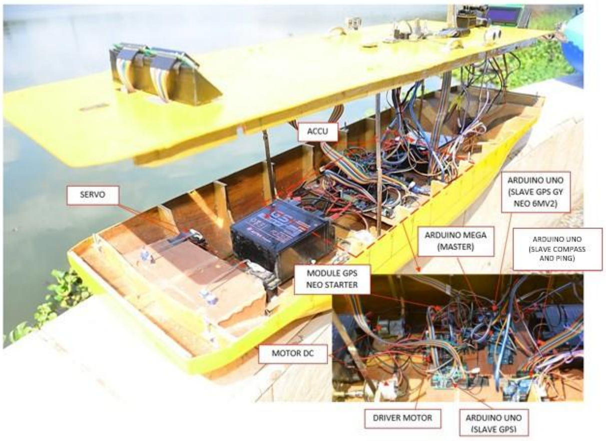

Figure 1. Ship Model with Equipment and Instrumen- tations for Free Running Experiment

ance between rudder increases [14]. These interaction effect should be investigated in advance and it should be considered in the future works.

The propeller thrust as function of thrust deduction factor, thrust coefficient as well as revolution and diameter of propeller were independently estimated based on formula proposed by Kijima, *et al*. [10]. The thrust coefficient was estimated based on statistical data of open water test for B series propeller [15]. Here, the thrust coefficient was modelled with polynomial regression as function of advance coefficient. The rudder forces and moment were calculated by using formula proposed by Kijima, *et al*. [10]. The propeller forces and moment of the starboard and portside rudders were different for the same rudder angle due to the different of those interaction coefficients.

Automatic Control System. The fuzzy logic based control was used to determine necessary rudder angle in order to avoid collision dangerous of ship in seaways. The necessary rudder angle is qualitatively determined based on combination between deviation of heading angle from the target point or obstacle and yaw rate by using the fuzzy logic rules shown in Table 3.

Here, NB means negative big, NM is negative middle, NS is negative small and ZE means zero. PB, PM, PS are positive big, positive middle and positive small, respectively. The sign of positive and negative are based on deviation between the actual heading angle and target heading angle refer to the global coordinate system shown in Figure 2. The positive deviation means that thenecessary yaw motion is clockwise, otherwise is negative deviation.

Classification of heading angle and yaw rate was carried out by evenly divided the possible heading angle and the yaw rate into each classes of fuzzy logic rules shown in Table 3. The possible heading angle was ranged between -180.0 degrees and +180.0 degrees, while the range of yaw rate was determined based on the yaw rate obtained in turning and zig-zag manoeuvring tests.

Table 3. Rules of Fuzzy Logic

yaw rate	NB	NM	NS	ZE	PS	PM	PB
NB	ZE	PS	PM	PB	PB	PB	PB
NM	NS	ZE	PS	PM	PB	PB	PB
NS	NM	NS	ZE	PS	PM	PB	PB
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NB	NB	NM	NS	ZE	PS	PM
PM	NB	NB	NB	NM	NS	ZE	PS
PB	NB	NB	NB	NB	NM	NS	ZE

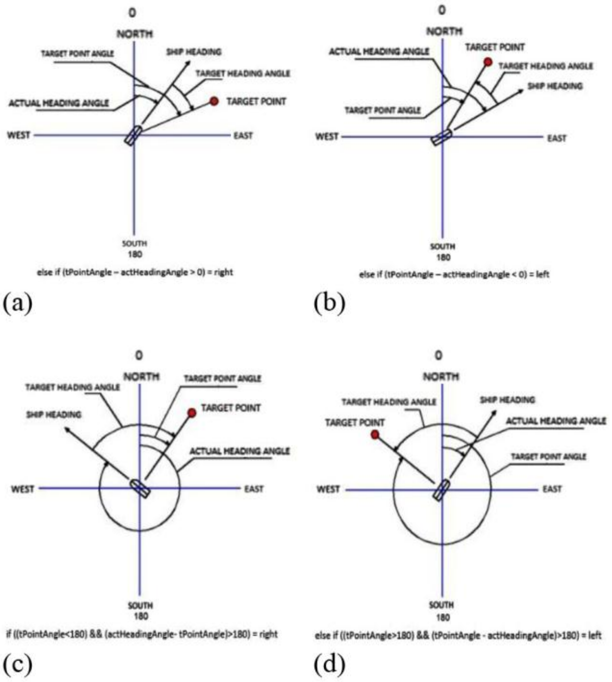

Figure 2. Deviation of Heading Angle and Direction of Yaw Rate

The actual heading angle was measured by inboard digital compass and the target heading angle was estimated based on actual heading angle and position of target point relative to the ship position as shown in Figure 2. The position of ship model was obtained from inboard GPS while the relative position and distance of obstacle were captured by three digital cameras installed in the model. In order to estimate the necessary rudder angle, the qualitative results of fuzzy logic process was converted to a real number as the rudder angle by using Mamdani Centroid method. This method can minimize time and cost in order to develop proper rules by generating and modifying the control rules by evaluating the system performance [16]. This method was used to design track-keeping autopilot for ship steering in seaways[17,18].

Experiment Procedures for Ship Collision Avoidance. The collision was assumed to occur when the model ship bumps an obstacle put with a certain distance in water area for experiment. Here, four fixed obstacles were used along the decided trajectory of ship model. The trajectory and position of those obstacles are shown in Figure 3. The coordinate system used for the trajectory and location of the obstacles were based on earth polar coordinate system as shown in Figure 3. The obtained trajectory from free running experiment was then converted into Cartesian coordinate system with conversion code in the automatic control program.

Young, *et al*. [19] used moving object named target ship to numerically simulate collision avoidance with 3 DOF mathematical equation of ship manoeuvring. Dynamic assumption of ship target or obstacles can be easily modelled in numerical simulation but it is very difficult in free running model experiment. Therefore, fixed target objects are used rather than moving objects.

The red circles shown in Figure 3 means the minimum distance from the obstacles for the control take action to change the rudder angle. This distance is taken to be the same as advance diameter of turning manoeuvring. This distance is different for different ship geometry depending on manoeuvring characteristic mainly the advance diameter.

Firstly, the ship model was set to reach the first obstacle indicated by CP1. When the distance of model from the obstacle is the same as or smaller than the permissible distance then the control changes rudder angle in order to avoid collision. After the model successfully passes the first obstacle, the model will go to the second target (CP2) with the same procedures until the model passes the last target point or obstacle. The trajectory, the heading angle, the rudder angle and the ship velocity obtained from the free running experiments were compared to the results of numerical simulation with the same automatic control system obtained by Fahmi [6].

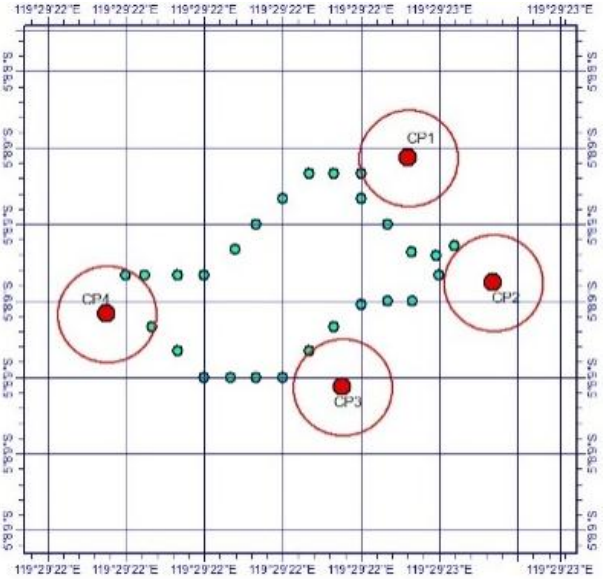

Figure 3. Trajectory and Position of Obstacles

3. Results and Discussion

Turning Circle Experiment. In order to obtain minimum distance between the model ship and the obstacle in which the control should take action, turning circle experiment was conducted. Figure 4 shows the turning trajectory obtained from the free running experiment with rudder angle of 35.0/35.0 degrees.

The advance diameter of the first turning manoeuvring was 3.49 of ship length between the perpendiculars and the tactical diameter was 3.65 of ship length between the perpendiculars. This turning manoeuvrability complied with the manoeuvring criteria of IMO [1] which was smaller than 4.0 of ship length between perpendicular. Based on these results of turning circle experiment, the minimum distance for the automatic control to take action for changing the ship heading angle in order to avoid collision was decided to be 3.50 of ship length between the perpendiculars mostly the same as the advance diameter.

The centre of turning manoeuvre changed but the turning diameter seemed to be the same between the first turning circle and the second turning circle. The turning trajectory shown in Figure 4 indicated that the external disturbances, especially the wind has significant effect on manoeuvring performances, mainly the turning ability of ship. A similar results regarding effect of windon turning manoeuvre has been found by [20]. The windforces induce a significant drift motion, therefore the turning diameter seem to be constant but its centre

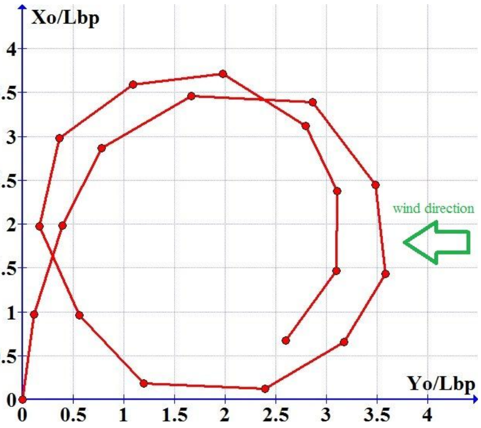

Figure 4. Turning Circle Manoeuvre

devolve depending on wind direction. The drift force-induced by wind depends on the windage area, wind velocity as well as the ship draught. This wind effect could be different depends on ship geometry. Therefore, effect of wind on automatic control especially on the design of control parameter should be taken into account.

Free Running for Collision Avoidance. Before starting the free running experiment for collision avoidance, performance of designed control system was evaluated base on response of ship dynamic. Here, the input was heading angle and the control system determined an appropriate rudder angle to change the heading angle to be the same as the target heading angle. Performance of the designed control system with input heading angle of 10 degrees is shown in Figure 5. Here, two different types of control: Proportional-Integral-Derivative (PID) controller and the fuzzy logic based controller were used. The transient response of system for fuzzy logic based control was smaller than that obtained from the PID control. The steady state response of PID control was longer than that of fuzzy logic based control.

Similar results regarding performance of fuzzy logic based control compared with the PID control had been obtained by Sanjaya, *et al.* [21]. The fuzzy logic base control is more effective compared with PID control for nonlinear system as well as system with past response. For linear system requires slow response, PID control ispreferable than the fuzzy logic base control. These previous researches did also not considered the external disturbance effect on autopilot design. Here, the fuzzy logic based control will be used for both free running experiment and numerical simulation.

The starting point of experiment was the origin of coordinate system shown in Figure 3 and Figure 7. Figure 6 shows the model run toward the first obstacle and its movement after passing an obstacle and moving to the next obstacle. The model returned to the origin after passing the last obstacle.

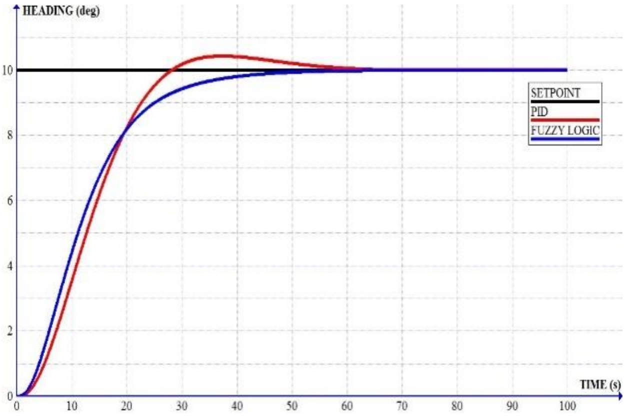

Figure 5. **Response of Automatic Control for Heading Angle of 10 Degrees**

The model trajectory, heading angle, rudder angle and the ship velocity obtained by both model experiment andnumerical simulation are shown in Figure 7–10, respectively. Figure 7 shows that the control has capability to avoid collision as indicated by the free running experiment and numerical simulation. Here, thetime interval for ship trajectory in model experiment was set to be 4 seconds, while in the numerical simulation the time interval was one second. Therefore, the number of data for ship trajectory obtained by numerical simlation was larger than that obtained by model experiment. In order to avoid difficulty for validation means, the heading angle, the rudder angle and the ship velocity shown in Figure 8 – 10 were the

Figure 6. Model Run between Obstacles

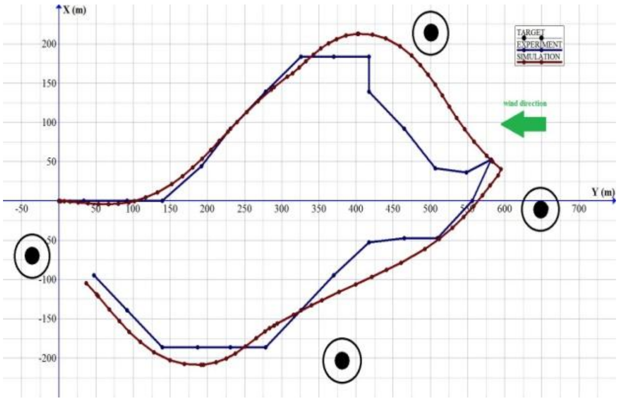

Figure 7. **Ship Trajectory Obtained by Experiment and Numerical Simulation**

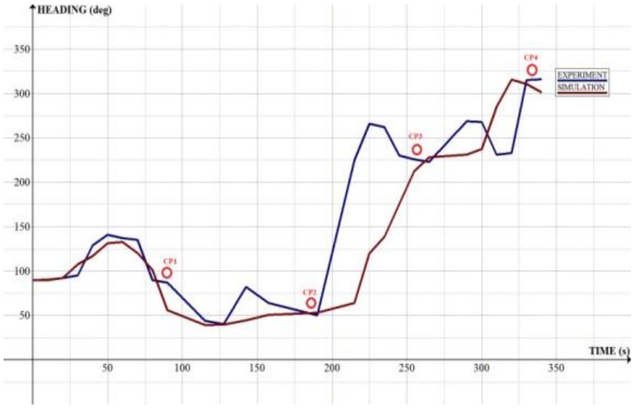

Figure 8. Heading Angle Obtained by Experiment and Numerical Simulation

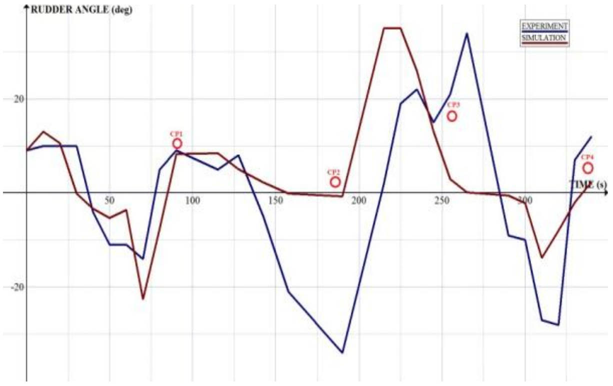

Figure 9. Rudder Angle Obtained by Experiment and Numerical Simulation

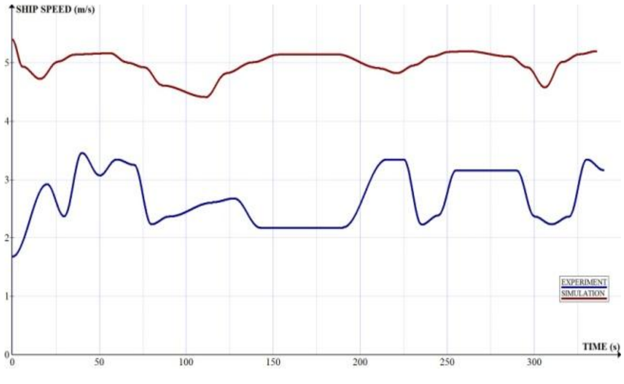

Figure 10. Velocity Obtained by Experiment and Numerical Simulation

values arround the point obtained from model experiment. The results of numerical simulation have good agreement with that of free running experiment. The significant different of ship trajectory appeared between the second target point and the third target point as well as in a certain region between the third target point and the fourth target point.

When the ship approached the first obstacle (CP1), the control in the model experiment changed the rudder angle in a longer distance compared than the numerical simulation. Here, the heading angle obtained by experiment was larger than that obtained by numerical simulation as shown in Figure 8. However, the rudder angle was not different significantly as shown in Figure 9. When the ship arrived in the second target point (CP2), the heading angle from model experiment was mostly the same as the heading angle of numerical simulation but the rudder angle of model experiment was larger than that of the numerical simulation. The distance of ship from the second target point (CP2) in the experiment was larger than that in the numerical simulation. Therefore, a larger rudder angle is neccessary in order to change the heading angle to approach the target point. When the ship passed the CP2, the rudder angle was significantly changed to portside in order to change ther heading angle toward the third target point (CP3). Here, the trend of both rudder angle and heading angle obtained from experiment and numerical simullationwere similiar even the the values were quite different.

Near the third target point (CP3), the heading angle of experiment and numerical simulation was similiar but the rudder angle was different. The different rudder angle occured due to the different ship position between experiment and numerical simulation when approached the CP3 as shown in Figure 7. In the fourth target point (CP4), the different of heading angle and rudder angle between experiment and numerical simulation was not significant.

The discrepancy between the experiment and the numerical simulation may be induced by wind effect during the free running experiment. Even the heading angle and the rudder angle were not significantly different especially between CP1 and CP2, the ship trajectory was significantly different. The discepancy of trajectory may occur due to drift motion induced by the wind with direction shown in Figure 7. The numerical simulation was conducted without effect of wind so that drift motion did not occur. The ship forward velocity of the model experiment was also smaller than that of the numerical simulation. Therefore, external disturbance such as wind and waves should be considered in design of ship automatic control system of ship as suggested by Lee, *et al*. [16]. The other factors may induce the different between model the model experiment and the numerical simulation are the accuracy of the distance between obstacles and the ship model obtained from the inboard camera. A more accurate method to estimate the distance between ship model and target point should be carry out in order to minimize such error in the future. The minimum distance to avoid collision dangerous in the numerical simulation was determined to be the same as the advance diameter of turning circle manoeuvre.

Trajectories of both free running experiment and numerical simulation were quite different with the decided trajectories between the obstacles as shown in Figure 7. The control used in the numerical simulation and the free running experiment were only designed to identify objects and to calculate their distance without considering the path reference to reach the obstacles. The minimum distance of model from the obstacle for the control to change the rudder angle was more than 3.50 of ship length between the perpendiculars following the turning circle manoeuvring test. Therefore, the ship model changed the heading angle to the next obstacle with distance quite long from the obstacle (3.50 of ship length between the perpendiculars).

These results also show that the subject ship still has capability to avoid collision even the minimum distance for control initiate to change the rudder angle was smaller than the advance diameter. The model trajectory was still quite far from the obstacles especially for the third and the fourth obstacles. For safety reason due to uncertainty of the external disturbance such as the wind and the wave effect, the advance diameter of turning manoeuvre may be an appropriate minimum distance for the control system introduces alteration of rudder angle in order to avoid collision risk in seaways.

For more details investigate effect of external disturbance on performance of automatic control, the decided trajectory should be included in free running experiment and numerical simulation. This is meant to evaluate ability of control system to maintain ship trajectory against the external disturbances. Numerical simulation with different wind velocity is important to perform in order to obtain maximum wind velocity in which the automatic control can work perfectly to follow the decided trajectory or avoid collision occurrence during ship operation. This information is important for ship master to decide operation model between automatic control and manual mode.

4. Conclusions

A free running model experiment with application of automatic control system for collision avoidance of ship in seaways has been conducted. The obtained result was compared with result of numerical simulation. Based on the results of free running experiment and discussions, some conclusions can be remarked as follows:The proposed method for free running model experiment may be adopted as a method for physically evaluated performance of a designed automatic control system for collision avoidance.The automatic control system may become an alternative solution to minimize collision dangerous of a ship in seaways at least to provide early warning when the ship in distance smaller than 3.50 of ship length between perpendicular as the permissible minimum distance against collision. The external disturbances such as wind and waves should be considered in design of automatic control system because these can significantly affect the manoeuvring performance of ships in seaways especially turning ability due to large drift motion.

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