SHIP MANOEUVRING BEHAVIOUR IN CROSSING CURRENT

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SUMMARY

Ship behaviour in a current is one of the classical problems in ship manoeuvrability. However, it is not yet fully investigated. The study is motivated by an assessment study on the ship navigation near-by a river lock where a relatively strong current exists, and simulations are done to demonstrate how the ship behaves in a current. As a result, relatively large drift angles are obtained, where the ship is around perpendicular to the current and the current speed is relatively large. In normal ship speed, the drift angle is almost less than 20° where a normal mathematical model based on lift theory can be applied, but even if the ship speed is not low, in presence of current, a mathematical model for low speed should be considered. The phenomena should more frequently occur, if the current is not uniform, and the way to calculate in such case is discussed.

NOMENCLATURE

A_R	Rudder area (m^2)
B	Breadth of ship (m)
b_R	Rudder breadth (m)
C_B	Block coefficient of ship (-)
D_P	Propeller diameter (m)
d	Draft of ship (m)
F_N	Rudder normal force (N)
F_{Na}	Apparent rudder normal force (N)
h_R	Rudder height (m)
I_{zz}	Yaw moment of inertia (kg m^2)
m	Ship mass (kg)
m_x	Added mass in surge (kg)
m_y	Added mass in sway (kg)
N	Yaw moment (N m)
N_H, N_P, N_R	Yaw moment components of hull, propeller and rudder (N m)
n	Propeller revolutions per minute (rpm)
P	Propeller pitch (m)
r	Angular velocity in yaw(deg/s)
$\dot{r}$	Angular acceleration in yaw(deg/s^2)
r'	Non-dimensional angular velocity (-)
t	Thrust deduction factor (-)
U_c	Current speed (m/s)
U_d	Drifting speed due to current (m/s)
U_R	Rudder inflow velocity (m/s)
U_{Ra}	Apparent rudder inflow velocity (m/s)
U'	Non-dimensional ship speed (-)
u	Speed in surge (m/s)
u_a	Apparent speed in surge (m/s)
u_{Ra}	Apparent speed of rudder in surge(m/s)
u_c	Current speed in surge (m/s)
$\dot{u}_a$	Apparent acceleration in surge (m/s^2)
v	Speed in sway (m/s)
v_a	Apparent speed in sway (m/s)
v_{Ra}	Apparent speed of rudder in sway (m/s)
v_c	Current speed in sway (m/s)
$\dot{v}_a$	Apparent acceleration in sway (m/s^2)
X	Surge force (N)
X_H, X_P, X_R	Surge force components of hull, propeller and rudder (N)
x_G	Centre of gravity in x-axis direction (m)
Y	Sway force (N)
Y_H, Y_P, Y_R	Sway force components of hull, propeller and rudder (N)
Z	Number of propeller blades (-)
α_R	Rudder inflow angle (deg)
α_{Ra}	Apparent rudder inflow angle (deg)
β	Drift angle of ship (deg)
δ	Rudder angle (deg)
Λ	Aspect ratio of rudder height to chord length (-)
ψ	Ship heading (deg)
ψ_c	Current direction (deg)
ψ_d	Drifting angle due to current (deg)

1. INTRODUCTION

In a narrow water channel/river where there is fast current/stream exists, ship cannot be operated in high speed and the ship motion has relatively large drift angle. To assess the safety of ship operation in such circumstances, it is important to simulate the ship motion in current/stream accurately. If there are some obstacles in waterway such as islands, shallow bottom/water splash, a lock or flood gate etc., the ship behaviour is quite complicated because of the current/stream near-by the obstacles. This paper aims to predict ship behaviour in such case. There are already some researches [1-6] mostly done in 1970s in Japan, because in Japan there are many strong current waterways mostly in an inland sea called "Setonaikai", due to the fact that there are strong ocean current as well as strong ocean tidal, there exists large difference of sea surface at the orifices between outer area and inland sea. This area is called as "Seto" in Japanese and from the ancient time, it is terrified by seamen. Therefore these researches [1-6] were done to analyze/prevent the accidents happened at such places. In these researches, they [2,3,4] treat mathematical model using apparent velocity due to the current. Even though they did not quote, this concept is probably first proposed by Crane [7]. He has also proposed to use cross flow model which can be applied for the calculation of ship motion in a non-uniform current, although he did not apply it for simulation.

Ogawa [4,5,6] used the shear flow model instead of the cross flow model. He [4] researched about the shear flow model numerically, and for validation of the model, he [5] conducted experiment. Then, the model is applied to actual problem [6]. Honda, *et al.* [1] studied the research based on real ship observation/measurement, and heading angle distribution between simulation and observation/measurement is compared. Iwai *et al.* [3] studied about the influence of current around the bridge pier for safe course-keeping of ship, and they [3] showed the dangerous zone is wide and the ship manoeuvring is rather effective to the reverse current. However, as their [1-6] research aim is to estimate a ship's motion in such a place, they did simulation based on the measured current distribution, and they did not draw general conclusion on the influence of the current.

Kashiwagi [8] used cross flow model for simulation of ship motion in a non-uniform current, following Crane's [7] concept.

Yang and Fang [9] have also worked for this subject, and proposed new distribution forms of hydrodynamic force and moment on the basis of wing theory. Their model is expressed following Ogawa [6] and Kashiwagi's [8] expression way, and Crane's [7] apparent speed concept is used.

In this paper, the basic behaviour of ship motion in a current will be discussed using apparent speed concept proposed by Crane [7]. For the main purpose of this paper, ship behaviour near-by a lock should be calculated using cross flow model, but at the same time, the importance of low speed manoeuvring model is pointed out. Actual simulation of the ship motion near-by a lock will be done based on the measured/estimated current distribution with mathematical model for low speed, although in this paper, it is not yet done.

2. SHIP MANOEUVRING MOTION IN CURRENT

2.1 MATHEMATICAL MODEL UNDER UNIFORM CURRENT

In this chapter basic mathematical model treating uniform current will be summarized.

Coordinate system and definition of symbols and their positive directions are shown in Figure 1. There are several expressions to express external forces and moment (X, Y and N) in eq. (1), but here they are generally described in terms due to hull (H), propeller (P) and rudder (R) as shown in eq. (2).

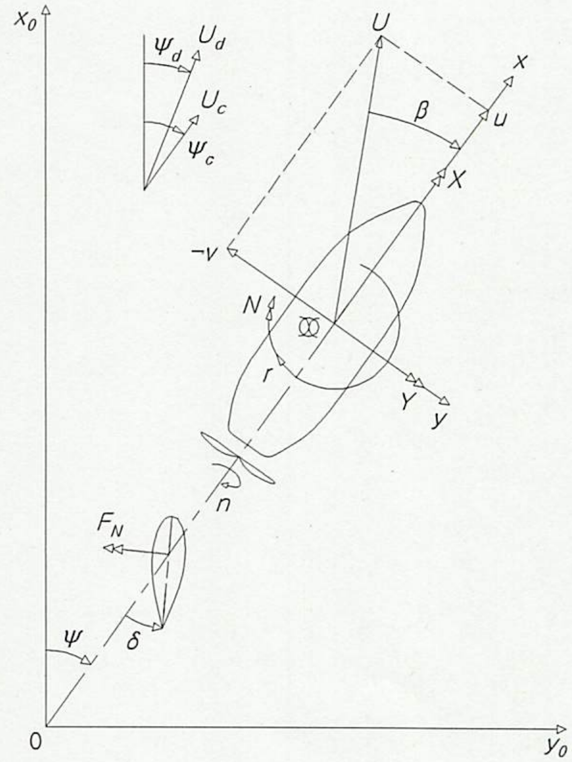


Figure 1: Coordinate system.

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

$$\left.\begin{aligned} X &= X_H+X_P+X_R \\ Y &= Y_H+Y_P+Y_R \\ N &= N_H+N_P+N_R \end{aligned}\right\} \quad (2)$$

In the expressions of each external force and moment, apparent speeds u_a and v_a are used as shown in eq. (3), instead of u and v respectively, when a current exists.

$$\left.\begin{aligned} u_a &= u+U_c\cos(\psi_c-\psi) \\ v_a &= v+U_c\sin(\psi_c-\psi) \end{aligned}\right\} \quad (3)$$

where U_c is current speed, ψ_c and ψ are the current directions and ship heading angle respectively. It is described, as shown in *e.g.* eq. (4). The detail expression is based on MMG model [10,11], but it is not unique and not necessary to be the same expression.

$$
\left.\begin{aligned}
X &= -\dot{u}_a m_x + v_a r m_y + X_{vv} v_a^2 \\
&\quad + X_{vr} v_a r + X_{rr} r^2 + X_{vvvv} v_a^4 \\
&\quad + (1-t)T - R \\
&\quad - (1-t_R) F_N \sin\delta \\
Y &= -\dot{v}_a m_y - u_a r m_x + Y_v v_a + Y_r r \\
&\quad + Y_{vv} v_a |v_a| + Y_{rr} r |r| \\
&\quad + Y_{vvr} v_a^2 r + Y_{vrr} v_a r^2 \\
&\quad - (1+a_H) F_N \cos\delta \\
N &= -\dot{r} J_z + N_v v_a + N_r r \\
&\quad + N_{vv} v_a |v_a| + N_{rr} r |r| \\
&\quad + N_{vvr} v_a^2 r + N_{vrr} v_a r^2 \\
&\quad - (x_R + a_H x_H) F_N \cos\delta
\end{aligned}\right\} \tag{4}
$$

where t is thrust deduction factor, T is thrust, and R is resistance of a ship. In the term of rudder force, t_R is effective wake coefficient, δ is rudder angle. F_N is rudder normal force as shown in eq. (5).

$$
\left.\begin{aligned}
F_N &= \frac{\rho}{2} A_R f_a U_R^2 \sin\alpha_R \\
U_R &= \sqrt{u_R^2 + v_R^2} \\
\alpha_R &= \delta - \tan^{-1}\left(\frac{-v_R}{u_R}\right)
\end{aligned}\right\} \tag{5}
$$

where A_R and f_α are rudder area and the gradient of the lift coefficient of rudder respectively, U_R is inflow velocity of rudder, and α_R is inflow angle. u_R and v_R are surge and sway speed at rudder. For more detail of u_R and v_R, refer [10,11]. In order to treat current, the concept of apparent speed which is shown in eq. (6), must be used for the U_R and α_R.

$$
\left.\begin{aligned}
u_{Ra} &= u_R + U_c \cos(\psi_c - \psi) \\
v_{Ra} &= v_R + U_c \sin(\psi_c - \psi)
\end{aligned}\right\} \tag{6}
$$

As a result, eq. (5) is transformed as eq. (7), the subscript N, a and R of F_{Na}, U_{Ra} and α_{Ra} means normal, apparent and rudder respectively.

$$
\left.\begin{aligned}
F_{Na} &= \frac{\rho}{2} A_R f_a U_{Ra}^2 \sin\alpha_{Ra} \\
U_{Ra} &= \sqrt{u_{Ra}^2 + v_{Ra}^2} \\
\alpha_{Ra} &= \delta - \tan^{-1}\left(\frac{-v_{Ra}}{u_{Ra}}\right)
\end{aligned}\right\} \tag{7}
$$

2.2 MATHEMATICAL MODEL IN NON-UNIFORM CURRENT

2.2 (a) Hydrodynamic Force and Momnet Acting on a Hull

In non-uniform current situation, lateral hydrodynamic force cannot be calculated properly using MMG model. Because of this problem, Ogawa [4,5,6] proposed the shear flow model as shown in eqs. (8,9,10). The lateral force Y_H and yaw moment N_H acting on a ship due to a current can be expressed as shown in eq. (8), if it is expressed in the distribution component.

$$
\left.\begin{aligned}
Y_H &= \int_{-L/2}^{L/2} y_H(\xi) d\xi \\
N_H &= \int_{-L/2}^{L/2} n_H(\xi) d\xi
\end{aligned}\right\} \tag{8}
$$

where the lateral force and moment distribution alongside longitudinal direction $y_H(\xi)$ and $n_H(\xi)$ can be expressed as eq. (9).

$$
\left.\begin{aligned}
y_H(\xi) &= h(v_a, r) f(\xi) \\
n_H(\xi) &= h(v_a, r) f(\xi) \xi
\end{aligned}\right\} \tag{9}
$$

where $h(v_a, r)$ is the lateral force distribution for given v_a and r, and $f(\xi)$ is defined as eq. (10).

$$
\int_{-L/2}^{L/2} f(\xi) d\xi = 1 \tag{10}
$$

On the other hand, Kashiwagi [8] proposed to use cross flow model originally proposed by Crane [7] for the lateral force and moment, which can be applied for a non-uniform current directly. The non-linear terms in Y and N expressions in eq. (4) are replaced with the cross flow models which are expressed as $Y_{NL}(v_a, r)$ and $N_{NL}(v_a, r)$ as shown in eq. (11), where v used in normal, cross flow model are replaced with v_a.

$$
\left.\begin{aligned}
Y_{NL} &= -C_D \int_{-1/2}^{1/2} |v_a(\xi) + \xi r| (v_a(\xi) + \xi r) d\xi \\
N_{NL} &= -C_D \int_{-1/2}^{1/2} |v_a(\xi) + \xi r| (v_a(\xi) + \xi r) \xi d\xi
\end{aligned}\right\} \tag{11}
$$

where C_D is drag coefficient of hull at drift angle is 90°. Yang and Fang [9] proposed a similar expression of $y_H(\xi)$ based on wing theory.

2.2 (b) Hydrodynamic Force Acting on a Rudder

In non-uniform current situation, U_c and ψ_c are different according to the position in space fixed coordinate system. Moreover, for hull and rudder, different two concepts of apparent speed are required. The apparent speed at hull have to be calculated using eq. (3), and the apparent speed for rudder have to be calculated using eq.

(6), where U_c, the current speed and ψ_c, the current direction is the function of the coordinate of the rudder in the space-fixed coordinate system 0-x_0y_0.

3. SIMULATION OF SHIP MANOEUVRING MOTION IN CURRENT

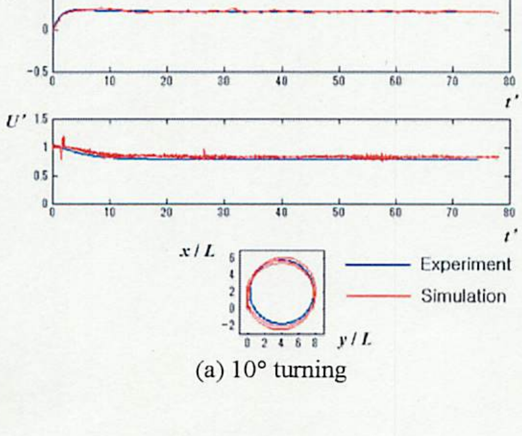
For the estimation of ship manoeuvring motion in a current, simulation studies are carried out. As the subject ship, Esso Osaka model is used, and the principal particulars are listed in Table 1. The simulation is conducted at ship speed is 0.495 m/s with various current speed.

Table 1: Principal particulars of subject model.

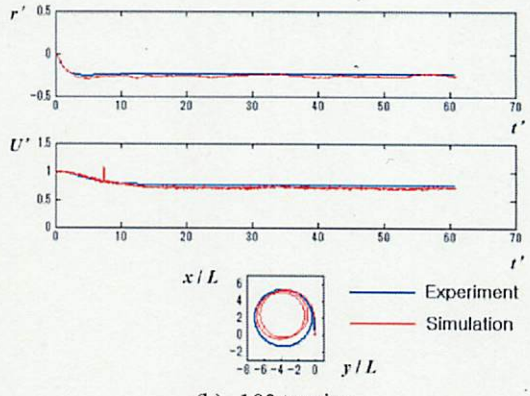
Hull	Length, L (m)	3.000
	Breadth, B (m)	0.489
	Depth, d (m)	0.201
	Block Coefficient, C_B	0.831
Propeller	Propeller Diameter, Dp (m)	0.084
	Pitch, P (m)	0.060
	No. of Blades, Z	5
Rudder	Rudder Breadth, b_R (m)	0.080
	Rudder Height, h_R (m)	0.128
	Rudder Area, A_R (m^2)	0.010
	Aspect Ratio, Λ	1.54

3.1 SIMULATION IN VARIOUS CURRENT CONDITIONS

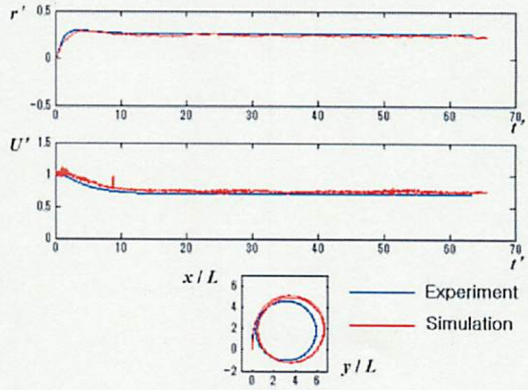
Before conducting the simulation in current, in order to validate the mathematical model and its coefficients, turning simulation is conducted in several rudder angle conditions without current, and results are compared with the free running experiment data as shown in Figure 2. They match well respectively, so the model and its coefficients are validated.



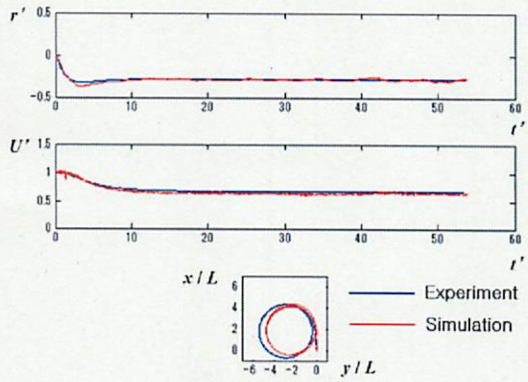
(a) 10° turning



(b) -10° turning



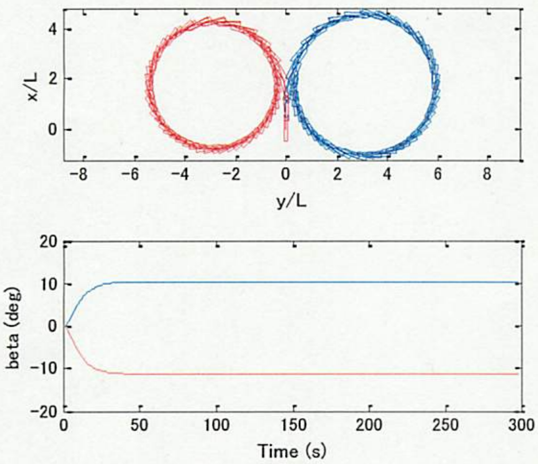
(c) 15° turning



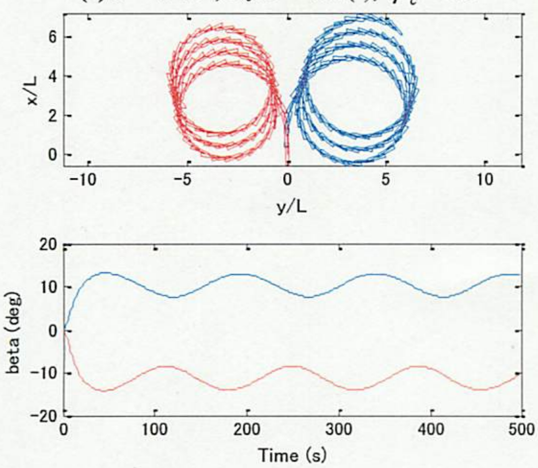
(d) -15° turning

Figure 2: The comparison of several turning motions between experiment and simulation.

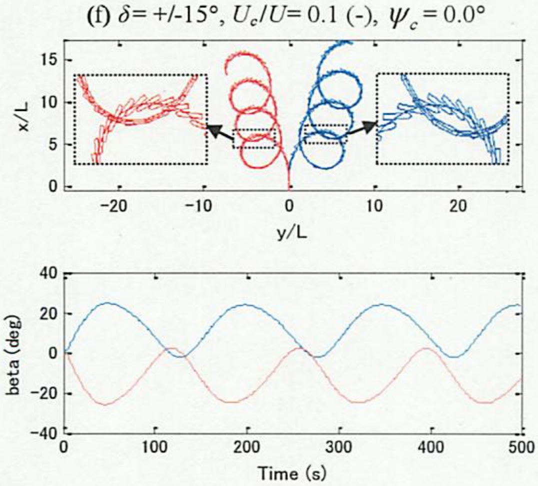
The simulation is conducted for rudder angle is 15° in various current conditions and the results are shown in Figure 3. Figure 3(e) is the result without a current for the comparison with others (f-h). The upper graph is the ship's trajectory and the lower graph is the time history of drift angle (β) respectively. The upper graph of Figure 3(e) is same with the trajectories of Figure 2(c-d), but drift angle is added for the comparison between others (f-h). It is found that the drift angle is saturated to around +/-10° in steady turning. In case of Figure 3(f-h), turning circle radius is almost same but drifting down stream side with slightly starboard side for starboard turning and vice versa for port turning. Looking inside the time history of the drift angle and enlarged part of the trajectories, it is also found that the drift angle fluctuates around the saturated value of the case (e) and the degree of the fluctuation is proportional to the current speed ratio to the ship speed. Due to this fluctuation, the ship has larger drift angle in down stream side (12 O'clock direction, if the turning trajectory is regarded as a clock) of a turning circle and vice versa in the upper stream side (6 O'clock direction) of a turning circle. On the other



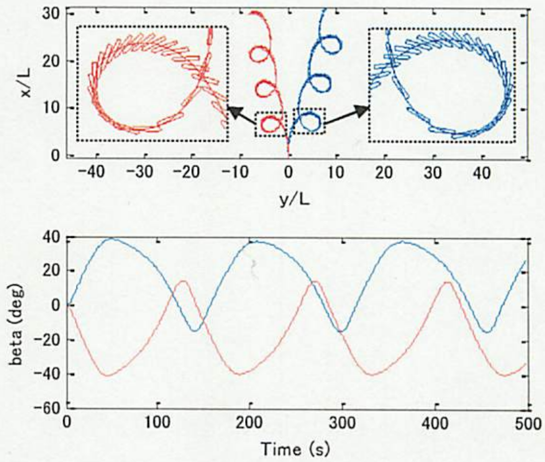
(e) δ= +/-15°, U_c/U = 0.0 (-), ψ_c = 0.0°



(f) δ= +/-15°, U_c/U= 0.1 (-), ψ_c = 0.0°



(g) δ= +/-15°, U_c/U = 0.5 (-), ψ_c = 0.0°



(h) δ= +/-15°, U_c/U = 1.0 (-), ψ_c = 0.0°

Figure 3: Simulation results in various current speed ratio conditions with current direction is 0°.

hand around 3 O'clock direction and 9 O'clock direction the drift angle is almost same with the value of the case (e). This asymmetry of the drift angle makes the *trajectory* to *drift* (which is not the same terminology of the ship drift angle and to be defined as *trajectory drift* [12]) starboard side for starboard turning and port side for port turning. Figure 4 shows the relation of the *trajectory drift* angle in term of $|\psi_d|$-ψ_c, where ψ_d is the *trajectory drift* angle and the current speed ratio to the ship speed. Figure 5 shows the relation of the *trajectory drift* speed of the trajectory defined as U_d in ratio to U_c and the current speed ratio to the ship speed.

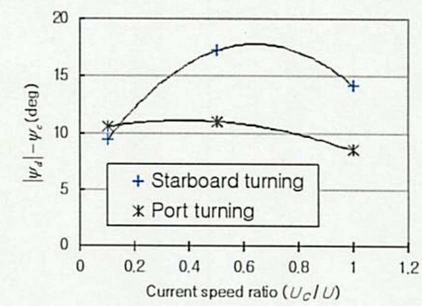


Figure 4: The relation between current speed ratio and drifting angle.

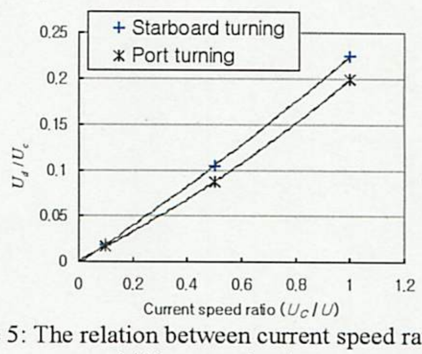


Figure 5: The relation between current speed ratio and drifting speed ratio.

From Figures 3-5, the following general descriptions of current influence to a ship motion in case of turning can be drawn.

(1) The ship *trajectory drifts* to the down stream side, when a ship makes turning in a uniform current, but slightly starboard side for starboard turning and vice versa for port turning. This tendency is also obtained by You and Rhee [13].

(2) The *trajectory drift* angle has not clear tendency, and different between starboard and port turnings with the current speed ratio to the ship speed, but roughly speaking, the difference of this value is not so large and around 10-17°.

(3) Contrary, the *trajectory drift* speed is almost proportional to the current speed ratio to the ship speed and not much different between starboard and port turnings.

(4) In a single turning circle, even if the *trajectory drifts*, the ship drift angle is different with the ship position in the circle. Around 12 O'clock, if the circle will be regarded as a clock, there exists larger drift angle and the value is almost proportional to the current speed ratio to the ship speed, while around 6 O'clock, the value is smaller than that of no current condition. If the current speed ratio to the ship speed exceeds 0.5, the maximum drift angle exceeds 20°. It suggests that in such large drift angle range due to current/stream, a normal mathematical model such as eq. (4) cannot be applied, but a low speed manoeuvring model should be used, because the normal mathematical model expresses the hydrodynamic forces and moment acting on a ship only within the drift angle range of about +/-20°.

For the detail of the low speed manoeuvring model Oh and Hasegawa [14, 15] summarized several models and compared their applicability. Calculating ship motions in non-uniform current and applying a low speed manoeuvring model, more preside ship behaviour in sophisticated current/steam condition can be obtained.

4. CONCLUSIONS

In the present study, ship manoeuvring in a current is reviewed and simulated. In various current speed ratios to ship speed, the influence of current is studied, and the obtained results are summarized below.

1) In most cases, if the current speed ratio to ship speed is not high, conventional mathematical model can express ship motion in current well.

2) Even if the ship speed is not so low, there are some current conditions where hydrodynamic forces/moment have to be treated considering low speed model.

3) The influence of low speed mathematical model and non-uniform current should be studied in the future for the case in river or in strong shear current.

4) The method can be also utilized for ship motion analysis under tsunami or some ship accident analysis in a river.

5) The influence of ship drifting in a current at turning motion is shown respective to current ship speed ratio.

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