A FUNDAMENTAL STUDY ON THE SHIP HANDLING SIMULATION OF TUG-BARGE AND PUSHER-BARGE SYSTEMS FOR RIVER SERVICE

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SUMMARY

Mahakam River in Indonesia has been famous for coal transport by tug-barge system (TBS) and many ships come and go in the narrow waterway. Since the number of ships is predicted to increase as the coal mining becomes more active, there is a big concern about the navigation safety in the heavier traffic situation in near future. Pusher-barge system (PBS) which has better manoeuvrability and easier handling rather than TBS is worthy of consideration as an alternative transport way. This mean of transport would be more suitable for the serpentine and congested river and the smoother and safer traffic flow could be expected. This study is still in the first stage. In this paper, assuming TBS and PBS sailing a S-shaped bend in Mahakam River, the manoeuvring motions and handling techniques of them are discussed. Meeting and overtaking simulations are also run to investigate the behaviour of collision avoidance of each system. Authors aim to make a fundamental study on the difference of the navigation state by the different way of transport.

NOMENCLATURE

ψ	Heading angle (deg)
β	Hull drift angle (deg)
δ	Rudder angle (deg)
u	Surge velocity (m s^{-1})
v	Sway velocity (m s^{-1})
r	Yaw rate (s^{-1})
m	Ship's mass (kg)
m_x	Added mass in surge (kg)
m_y	Added mass in sway (kg)
I_Z	Moment of inertia in yaw (kg m^2)
J_Z	Added moment of inertia in yaw (kg m^2)
X	Surge force (N)
Y	Sway force (N)
N	Yaw moment around C_G of ship (N m)
R_0	Resistance (N)
ρ	Water density (kg m^{-3})
L_{OA}	Length overall (m)
L_{PP}	Length between perpendiculars (m)
d	Draft (m)
U_C	Absolute velocity of river flow (m s^{-1})
ψ_C	Absolute direction of river flow (deg)
U_a	Absolute ship's velocity through water (m s^{-1})
u_a	Surge velocity through water (m s^{-1})
v_a	Sway velocity through water (m s^{-1})
T_S	Tow line tension (N)
θ	Deflection angle of tow line (deg)
φ	Difference of heading angle b/w tug and barge (deg)
l	Length of tow line (m)
a_1	Distance to towing point from C_G of tug (≤ 0) (m)
a_2	Distance to towing point from C_G of barge (≥ 0) (m)
P	Proportional gain for rudder control (-)
D	Differential gain for rudder control (-)
ψ_t	Heading angle for the next waypoint (deg)

1. INTRODUCTION

A barge which is defined as a floating body with a flat bottom is often used for carrying a large amount of cargos in rivers or inland waterways. It is not only self-propelled by itself but also towed by a tug or pushed by a pusher in many cases. As one of good examples, Mahakam River which is the largest river in East Kalimantan, Indonesia, has been famous for coal transport by tug-barge system (TBS) (see Fig. 1). Because the area around this river is so rich in coal resources that the development of mines are still active and the river transport has been mainly used for coal carries. Based on the good prospect for long minable years, the demand for barges sailing in Mahakam River is likely to increase in near future. However, crash accidents into bridge girders or other barges have been reported, which was supposed to be due to the lower manoeuvrability of tug-barge system under the flow stream pressure. So there is a big concern that the current transport system could be still safe and useful even in the heavier traffic situation in future. The introduction of pusher-barge system (PBS) could be one of solutions. Since PBS has better manoeuvrability and easier handling rather than TBS, it would be suitable for safe navigation in a serpentine river or a congested area where ship has to pass through many others.

The final goal of this research project is aim to discuss the navigation safety of TBS and PBS in Mahakam River using the Marine Traffic Simulator System (MTSS) which has been developed by Hasegawa et al. (e.g. [1][2]). In the first stage, authors make a simulation study on the manoeuvring motions and handling techniques of those ships sailing a sharp bend of the river. For this purpose, MTSS is modified by updating the manoeuvring model to the sophisticated one. Not only the effectiveness of the introduction of PBS is verified but also the possibility of the increase of barge size is investigated from the view point of controllability. The behaviour of collision avoidance when meeting and overtaking around a anchored ship is also discussed.


(https://maps.google.co.jp/)   (http://www.panoramio.com/photo/83299686)

Fig. 1 A photomap of Macadam River in East Kalimantan, Indonesia (left) and a photo of coal transport by Tug-Barge System (right)

2. SIMULATION METHOD

2.1 MARINE TRAFFIC SIMULATION SYSTEM

Hasegawa has developed an automatic collision avoidance algorithm based on fuzzy reasoning for many years and programmed it to Marine Traffic Simulation System. So called MTSS can simulate marine traffic flow in which ships reproduced by OD data head for the destination via arbitrary waypoints avoiding collisions with each other. All of ships move based on a simple manoeuvring mathematical model which includes parameters related to the ship type and specifications. The timing of collision avoidance and a following action are automatically decided by fuzzy reasoning.

MTSS is roughly composed of four main parts such as [A]Ship generation, [B]Decision of navigation mode i.e. normal, avoidance, or overtaking manoeuvre, [C]Decision of action plan i.e. heading course, rudder angle and speed control, and [D]Calculation of ship manoeuvring motions. In this study, the manoeuvring mathematical model incorporated into [D] was updated into the sophisticated model and explained in the next section. More details of other parts should be referred to the references such as [1][2].

2.2 MATHEMATICAL MODEL FOR SHIP MANOEUVRING

2.2 (a) Outline of mathematical model

MTSS has been used for safety assessment of marine traffic in a congested sea area and the result such as the number of near misses and collisions has been analysed statistically. The first order Nomoto model so called KT model [3] which can generally predict ship manoeuvring motions in spite of the simplicity is useful for such a statistical analysis because of the less computation time. However, the complicated condition where the barge is towed by the tug cannot be expressed by KT model and the influence of flow stream on the hull forces cannot be considered, either. In order to discuss the difference of the ship handling between TBS and PBS for river service, a more advanced mathematical model which can simulate the manoeuvring motions as precisely as possible was needed. For this reason, MMG model [4], one of standard mathematical model for ship manoeuvring today, was newly programmed into MTSS.

2.2 (b) Equations of motions

The coordinate system is shown in Fig. 2. $O\text{-}x_0y_0z_0$ is the right-hand space-fixed coordinate system with x_0y_0 plane referring to the water surface. $G\text{-}xyz$ is the right-hand ship-fixed coordinate system in which the origin is defined at the centre of gravity of ship. x and y are the ship's forward and starboard direction. The variables with subscript "2" belong to the barge towed by the tug in the case of TBS. Assuming a ship sailing a river, the motion equations for surge, sway and yaw are defined as follows.

$$\left.\begin{aligned}&(m+m_x)\dot{u}-(m+m_y)v_a r\\&\qquad=-(m+m_x)U_C r\,sin(\psi_C-\psi)+X\\&(m+m_y)\dot{v}+(m+m_x)u_a r\\&\qquad=(m+m_y)U_C r\,cos(\psi_C-\psi)+Y\\&(I_Z+J_Z)\dot{r}=N\end{aligned}\right]\tag{1}$$

Where

$$\left.\begin{aligned}u_a&=u+U_C\cos(\psi_C-\psi)\\v_a&=v+U_C\sin(\psi_C-\psi)\end{aligned}\right]\tag{2}$$

X, Y and N are defined by summing force components as follows.

$$\left.\begin{aligned}X&=X_H+X_R+X_P+X_T\\Y&=Y_H+Y_R+Y_T\\N&=N_H+N_R+N_T\end{aligned}\right]\tag{3}$$

Each subscript "H", "R", "P" signifies the force/moment acting on the hull, rudder and propeller respectively. The force with subscript "T" means the towing force. So in the case of PBS, the force terms with subscript "T" should be eliminated. Meanwhile, the force terms with "R" and "P" should be eliminated from the equations of the barge of TBS.

2.2 (c) Hull force

The hull force/ moment is defined by the following polynomial expression.

$$\left.\begin{aligned}X_H&=(\rho L_{OA}dU_a^2/2)\{-R_0'+X'_{vv}{v'_a}^2+X'_{vr}v'_ar'+X'_{rr}{r'}^2\}\\Y_H&=(\rho L_{OA}dU_a^2/2)\left\{\begin{matrix}Y'_vv'_a+Y'_rr'+Y'_{vvv}{v'_a}^3+Y'_{vvr}{v'_a}^2r'\\+Y'_{vrr}v'_a{r'}^2+Y'_{rrr}{r'}^3\end{matrix}\right\}\\N_H&=(\rho L_{OA}^2dU_a^2/2)\left\{\begin{matrix}N'_vv'_a+N'_rr'+N'_{vvv}{v'_a}^3+N'_{vvr}{v'_a}^2r'\\+N'_{vrr}v'_a{r'}^2+N'_{rrr}{r'}^3\end{matrix}\right\}\end{aligned}\right]\tag{4}$$

Where

$$U_a=\sqrt{u_a^2+v_a^2}\tag{5}$$

Where the hydrodynamic force derivatives e.g.X_{vv}, Y_v, N_r represent the magnitude of force and moment due to the manoeuvring motions such as sway or yaw or coupled motion of them. Note the variables used in the polynomials enclosed in braces are non-dimensional and they are distinguished by putting $'$.

2.2 (d) Rudder force and propeller force

The mathematical model of rudder and propeller forces is the same as Yasukawa et al. [5] and Koh et al. [6], which were based on the standard MMG model [4].

2.2 (e) Towing force

A tow line is assumed to be always tightened under high tension so it can be considered as a truss which doesn't stretch. The mathematical model of the tow line tension was proposed by Shigehiro [7] as follows

$$T_S = X_{T2}\cos(\varphi-\theta) + Y_{T2}\sin(\varphi-\theta) \tag{6}$$

Where

$$\varphi = \psi - \psi_2 \tag{7}$$

The deflection angle is solved by the following equation of motion.

$$\begin{aligned}\ddot{\theta} = &\frac{\{m_2(\dot{v}_2 + u_2 r_2) + m_2 a_2 \dot{r}_2\}\cos(\varphi-\theta)}{m_2 l} \\ &- \frac{\{m_2(\dot{u}_2 - v_2 r_2) - m_2 a_2 r_2^2\}\sin(\varphi-\theta)}{m_2 l} \\ &- \frac{(\dot{u} - vr - a_1 r^2)\sin\theta + (\dot{v} + ur + a_1\dot{r})\cos\theta}{l} + \dot{r}\end{aligned} \tag{8}$$

For example, the towing forces and moment acting on the barge can be expressed as follows.

$$\left.\begin{aligned} X_{T2} &= T_S\cos(\varphi-\theta) \\ Y_{T2} &= T_S\sin(\varphi-\theta) \\ N_{T2} &= a_2 T_S\sin(\varphi-\theta)\end{aligned}\right\} \tag{9}$$

2.2 (f) Rudder control for course keeping:

It is said that PD control has similarity to human judgement and behaviour. So the rudder control for course keeping is followed by the following equation.

$$\delta = P(\psi_t - \psi) - Dr' \tag{10}$$

In the case of TBS, the proportional control with respect to the deviation of the heading angle between the tug and barge is added. Besides, the differential control for the yaw rate of barge relative to that of tug is also considered.

$$\delta = P(\psi_t - \psi) - Dr' + P_2(\psi_2 - \psi) - D_2(r_2' - r') \tag{11}$$

3. TBS AND PBS FOR RIVER SERVICE

3.1 MODELLING OF TBS AND PBS

Japan coal energy center (JCOAL) published the investigation report of coal transport in East Kalimantan, Indonesia [8]. In this report, the standard specifications of TBS engaged in coal transport in Mahakam River were investigated by hearing surveys. It says 8000 DWT barges are mainly used and their size is about 90m x 25m x 5m. The length of tug is about 30m and the length of towing cable is from 50m to 70m. So the total length of TBS reaches approximately 190m at the longest. It seems difficult to increase the barge size due to the serpentine river with a narrow width and shallow draft, so the barge size has been empirically restricted.

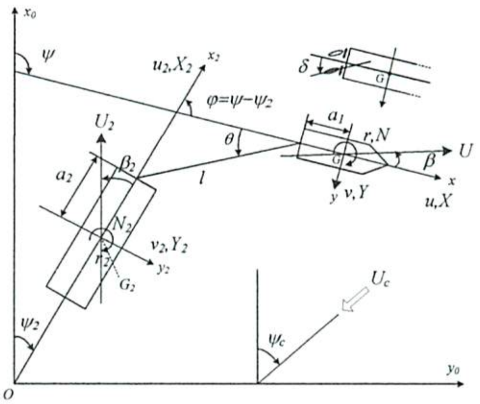

Fig.2 Coordinate systems and definition of each variable

The use of PBS could be a fundamental solution of this problem. Since the towing cable is not needed any more, the total length of PBS would be much shorter than TBS and the barge size would be more flexible. In this view point, three of barges with different load capacity i.e. 8000 DWT, 10000 DWT and 12000 DWT are conceptually sketched in the report [8] as shown in Fig.3. Regarding the service speed, it is said TBS is operated at 4 knot for safety. Meanwhile, PBS would be expected to increase the service speed to 6-8 knot because of the better manoeuvrability.

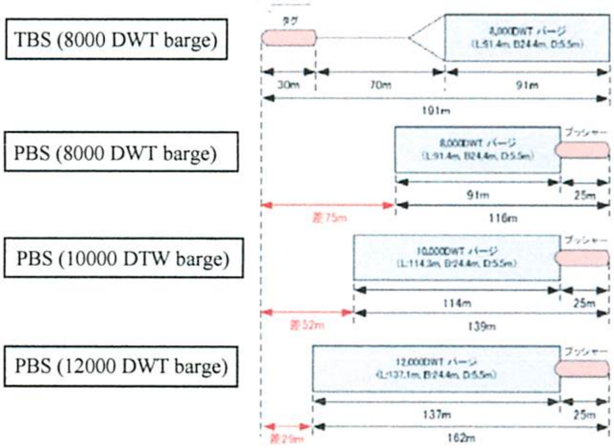

Fig.3 Illustration of a common TBS and conceptual designs of PBS with three different barge load conditions [8]

In this study, authors created rough computation models of a TBS and three PBS with similar dimensions specified in that report and they were used for analysis. The 3D computation models are shown in Fig. 4. Their

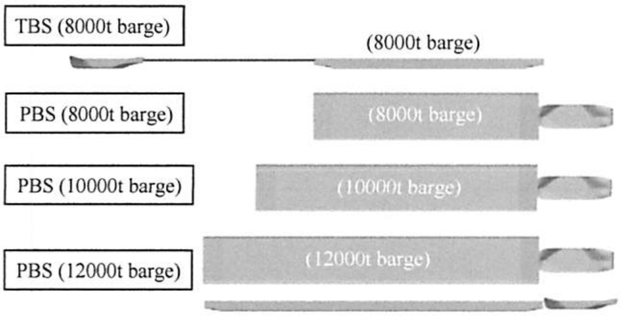

Fig.4 Computation models of TBS and PBS with three different barge load conditions

principal dimensions are listed in Table 1. Three barges with the displacement tonnage of 8000 t, 10000 t and 12000 t were considered. The tug/pusher was assumed to install twin screws and twin rudders. As for TBS, the cable length was assumed 70m and the barge was towed at only one point. The non-dimensional radius of gyration in yaw of all boats is assumed 0.25.

3.2 PREDICTION OF FORCE COEFFICIENTS

The hydrodynamic forces acting on the 1/50 scaled bare hulls in steady-state manoeuvres in the range of $|\beta| \leq 20^{\circ}, |r'| \leq 0.8$ were calculated by CFD method, OpenFOAM ver.2.3.0 [9]. The resistance and all of derivatives except for N_r' included in eq. (4) were identified by applying the least square method to the results of calculation. N_r' was estimated by the regression equation proposed by Yasukawa et al. [5] because it was derived from experimental results of multi pusher-barge systems so considered to be more reliable. They all are listed in Table 2. Note the derivatives with respect to r' are defined at the center of gravity of ship. Added masses and added moment of inertia are also listed in this table, which were estimated by Motora chart (e.g. [10]) for the tug and Yasukawa regression equation [5] for others. Extra parameters used in the mathematical model for the rudder and propeller performances were given as shown in Table 3. The meanings of each parameter should be referred to [4].

Table 1 Principal dimension of tug/pusher, barges and PBS

Item	Tug/Pusher	Barge(8000 t)	Barge(10000 t)	Barge(12000 t)	PBS(8000 t)	PBS(10000 t)	PBS(12000 t)
L_{OA} (m)	30	91.44	113.57	135.73	121.44	143.57	165.73
L_{PP} (m)	29.63	-	-	-	-	-	-
B (m)	10	19	19	19	19	19	19
d (m)	3.7	4.75	4.75	4.75	4.75	4.75	4.75
Displ. (t)	661.84	8000	10000	12000	8661.84	10661.84	12661.84
C_b	0.60	0.97	0.98	0.98	0.79	0.82	0.85
lcb from AE (m)	16.86	45.72	56.78	67.86	71.99	83.22	94.42

Table 2 Resistance coefficient, hydrodynamic derivatives and added mass coefficients

Item	Tug/Pusher	Barge(8000 t)	PBS(8000 t)	PBS(10000 t)	PBS(12000 t)
R_0'	0.0602	0.1055	0.0893	0.0804	0.0714
$X_{\beta\beta}'$	-0.0405	-0.2863	-0.1007	-0.0496	-0.0514
$X_{\beta r}' - m_y'$	-0.2859	-0.0591	0.0132	0.0056	0.0074
X_{rr}'	-0.1039	-0.1009	-0.0409	-0.0313	-0.0248
Y_{β}'	0.3921	0.3583	0.2001	0.1915	0.1874
$Y_r' - m_x'$	-0.0013	-0.0083	-0.0387	-0.0258	-0.0026
$Y_{\beta\beta\beta}'$	0.6254	0.8908	0.7416	0.7329	0.8912
$Y_{\beta\beta r}'$	-0.2771	0.2543	0.1372	0.0753	0.0353
$Y_{\beta rr}'$	0.2936	0.3015	0.2557	0.2651	0.1973
Y_{rrr}'	-0.0266	-0.0239	0.0400	0.0317	-0.0021
N_{β}'	0.1637	0.1182	0.0936	0.0883	0.0849
N_r'	-0.0724	-0.0477	-0.0424	-0.0399	-0.0381
$N_{\beta\beta\beta}'$	-0.0820	-0.1647	-0.0070	0.0507	0.0040
$N_{\beta\beta r}'$	-0.0001	-0.1215	-0.1876	-0.2115	-0.2130
$N_{\beta rr}'$	0.0244	0.0454	0.0301	0.0196	0.0219
N_{rrr}'	-0.0090	-0.0236	-0.0272	-0.0189	-0.0143
m_x'	0.0415	0.0157	0.0111	0.0089	0.0073
m_y'	0.3659	0.1748	0.1372	0.1195	0.1066
J_z'	0.0089	0.0076	0.0063	0.0057	0.0053

Table 3 Extra parameters used in the mathematical model for ship manoeuvring

symbol	value	symbol	value
t	0.18	a_H	0.2
w_{P0}	0.27	x_H/L_{OA}**	-0.45
w_{Pmin}	0.2	ε	1
C_1	-50	γ_R	0.6
$l_P/L_{PP(pusher)}$*	-0.48	l_R/L_{OA}**	-1.0

* TBS/PBS: Non-dimensional distance from midship of tug

** TBS: Non-dimensional dist. from midship of tug /PBS: That from midship of PBS

3.3 TURNING PERFORMANCE

In order to investigate the fundamental turning performance of the target TBS and PBS with a 8000t barge, the turning tests at 6 knot were simulated and the results in real scale are shown in Fig.5. The trajectories with ship sketches every 50 seconds are also shown in Fig.6. Although the diameter of circle looks similar between TBS and PBS in the case of 35deg turning, the difference of the advance is much significant. Because such a small tug is easy to handle, the tug starts turning soon after steering. Meanwhile, the turning of the tug is disturbed by following the towed barge which has higher displacement so the turning circle is bigger around the initial position. The results of 20deg turning shows the advance of TBS is much shorter than that of PBS as well. The turning circle becomes slightly bigger and seems to shift rightward.

The effect of the barge size of PBS on the turning performance is investigated next. The trajectories of 35degturning are compared in Fig.7. With increase of the barge size, the turning circle becomes larger. The advance and tactical diameter are summed up in Table 4. In this table, the estimated values presented by Maimun et al. (Table5 of [11]) who conducted the PMM test with a 1/50 scale-model of PBS with the 7503m^3 (L_{OA}:95m, B:19m, d:4.75 m, C_b:0.88) barge and simulated the real-scale turning is also added for reference. Note each dimension is similar as the author's 8000 t barge. Although the hull form and the rudder-propeller system are different between them, the turning performance looks close each other. It could become validation of the mathematical model for simulating the manoeuvring motions of PBS with a 8000 t class barge.

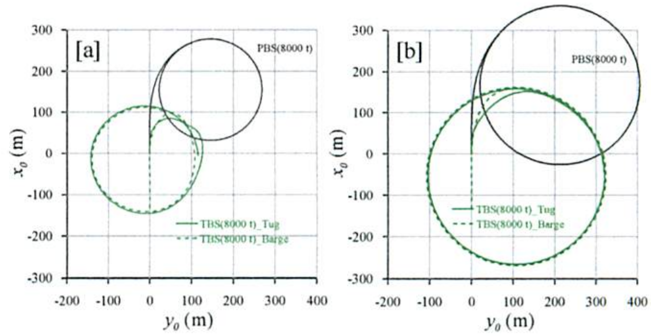

Fig.5 Comparison of turning trajectories between TBS and PBS:[a] δ = 35deg, [b] δ = 20deg

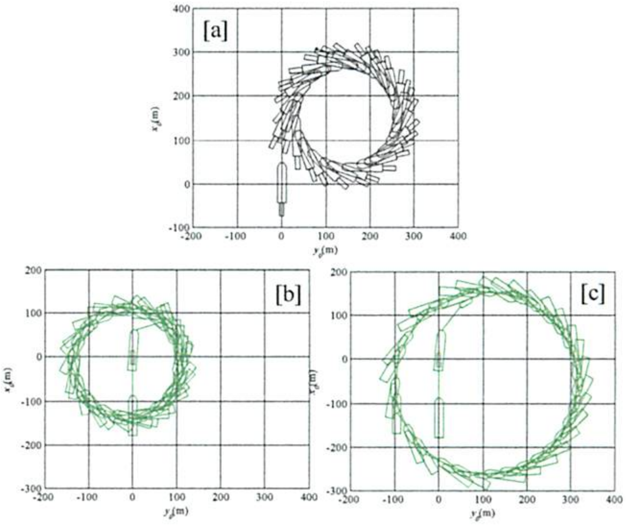

Fig.6 Turning trajectories with ship sketches every 50 seconds: [a] PBS δ = 35 deg, [b] TBS δ = 35 deg, [c] TBS δ = 20 deg

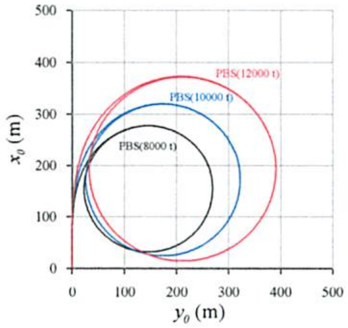

Fig.7 Comparison of turning trajectories among PBS with different sizes of the barge such as 8000 t, 10000 t and 12000 t

Table 4 Advance and tactical diameter of PBS in 35deg turning

Indices	Maimun et al.[11]	PBS(8000 t)	PBS(10000 t)	PBS(12000 t)
Advance (m)	254*	269.0	310.1	360.7
Tactical diamter (m)	265*	261.0	312.8	378.8

* The values were picked up from Table 5 of Maimun et al. [11]

4. MANOEUVRINGSIMULATION OF TBS AND PBS PASSING A S-SHAPED BEND

4.1 OVERVIEW OF MAHAKAM RIVER

Mahakam River is one of interesting rivers because it is influenced by tides and tidal currents from the Makassar Strait. So some field surveys or numerical studies by the hydrodynamical model have been made so far. One of them (Fig.11 of [12]) showed the time-series of mean flow velocity observed from the location near Samalinda in April. It indicates the maximum sub tidal flow velocity is about 0.8m/s. Since this river is serpentine as shown in Fig.1, a sailing ship has to manoeuvre carefully under the flow stream pressure, avoiding collisions against bridge girders or meeting/overtaking ships. Especially, the section from Mahulu Bridge to Mahkota Bridge which is located in the upstream from Port of Samalinda is considered to be one of critical locations. A pilot has to go on the boat during sailing through this section and an assist-tug has to be arranged behind the barge. They are needed for safe operation of TBS but would be inefficient in the view point of the smooth traffic flow.

In the next section, the sharp bend around Mahulu Bridge is focused on and the manoeuvring behaviour or handling technique of TBS and PBS are compared. Although an assistant tug of TBS was not modelled and obstructions such as bridge girders were not set in the simulation, the difference of the difficulty in sailing through such a S-shaped bend between different transport ways could be discussed.

4.2 SIMULATION RESULT OF TBS

4.2 (a) Influence of the rudder control gains

TBS towing a8000t barge is the first target for simulation. Changing the rudder control gains related to the barge motions i.e. P_2 and D_2 while P and D are always 1, the influence of them on the manoeuvring behaviour at 4 knot is discussed. U_c was assumed as 0m/s here. Fig.8 shows the trajectories every 50 seconds. Figs.9 and 10 shows the time-series of surge speed, hull drift angle, yawing rate, heading angle and rudder angle in the case of P_2=D_2=0 and 1 respectively. A solid line is for the tug and a break line for the barge. The green circles marked in Fig.8 mean the locations of waypoint.

In the case of P_2=D_2=0 where the tug operator doesn't have any concerns about the towing barge behind at all, the barge is periodically oscillated with a large amplitude all the time. The tug also experiences the periodic oscillation with a phase lag from the barge. So the tug seems to face the significant difficulty to tow the barge stably. When adding the proportional and differential control gains of the barge i.e. P_2=D_2=1 which means the operator is sensitive to the deviation of heading angle between the tug and barge and the relative yawing rate of the barge, the periodic oscillation can be reduced successfully and smoother manoeuvring behaviour can be achieved. But it should be noted that the barge has a relatively large drift angle for a long period of time and the rudder is kept controlling sensitively. In consideration of the actual operation of TBS, the tug operator always need to keep monitoring the towing barge in order to reduce a slewing motion. It would be stressful in such a narrow waterway.

4.2 (b) Influence of the flow pressure

The trajectory and time-series of TBS with all rudder control gains 1 under the condition of U_c=0.8 m/s are shown in Figs. 11 and 12 respectively. In this simulation, the river was simply assumed to flow along both side banks in parallel and the flow angle in the middle of the river was linearly interpolated. Compared with the case of U_c= 0m/s, the barge is significantly drifted due to the flow pressure all through the S-shaped bend regardless of the active rudder control. It indicates TBS might not pass through the bridge girders without any collisions and it surely needs the assist-tug behind the barge for safety.

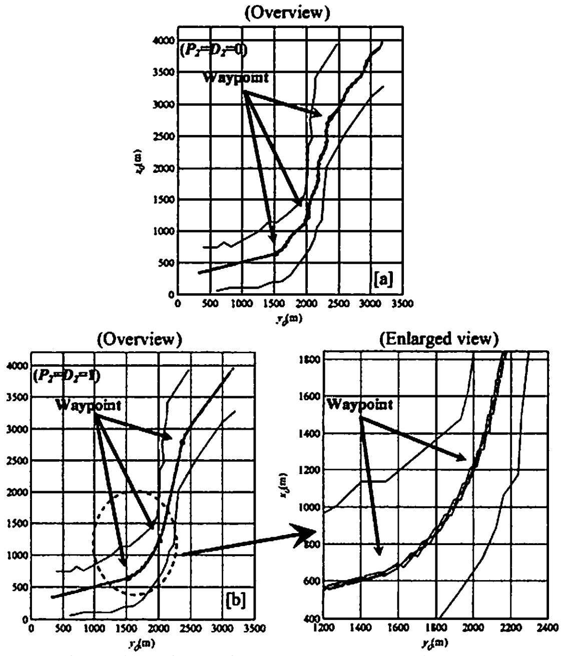

Fig.8 Trajectories of TBS in U_c=0m/s with different rudder control gains: [a] P_2=D_2=0, [b] P_2=D_2=1

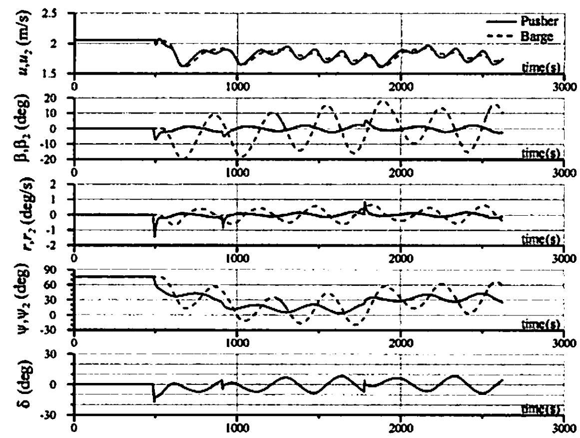

Fig. 9 Time-series of manoeuvring behaviour of TBS in U_c = 0 m/s with P_2 = D_2 = 0

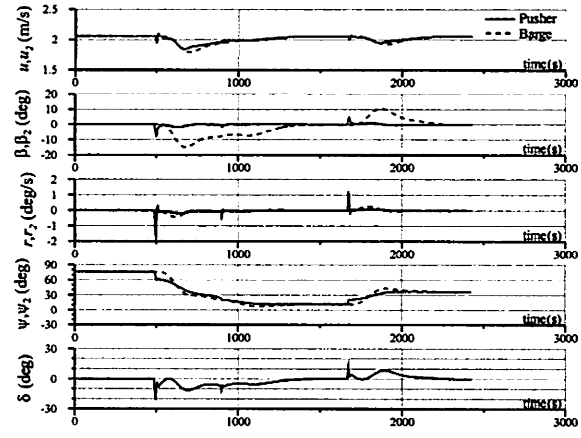

Fig.10 Time-series of manoeuvring behaviour of TBS in U_c=0m/s with P_2=D_2=1

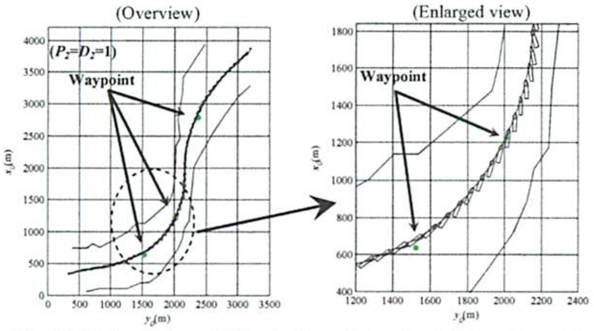

Fig.11 Trajectories of TBS in U_c = 0.8 m/s with P_2 = D_2 = 1

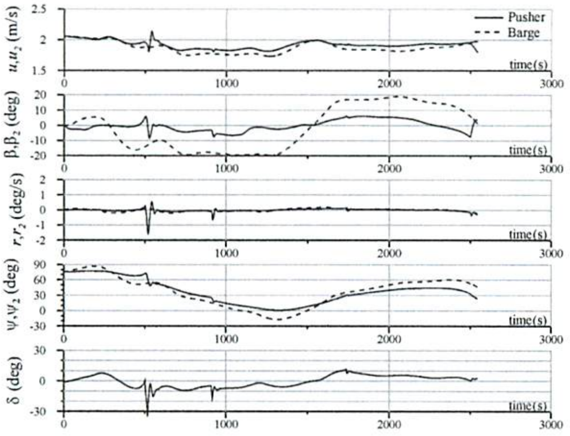

Fig.12 Time-series of manoeuvring behaviour of TBS in U_c=0.8m/s with P_2=D_2=1

4.3 SIMULATION RESULT OF PBS

PBS which pushes each 8000t, 10000t and 12000 t barge at 6 knot was the next target for simulation. Fig.13 and 14 shows the trajectories and manoeuvring behaviours of those PBS with P=D=1 passing the S-shaped bend. They were simulated without the river flow i.e. U_c = 0 m/s. With focus on the case of pushing the 8000t barge first, no slewing motion is observed and the motion induced by the turning manoeuvre is smoothly converged soon. In this view point, PBS seems to be easier to handle than TBS and contributes to the manoeuvring safety. With increase of the barge size to 10000t and 12000t, the initial development of yawing rate and heading angle is slower. That results in the larger turning diameter and makes the trajectory close to the bank. Especially when pushing a 12000t barge, it seems that PBS needs to start steering earlier in order to pass the first waypoint exactly.

Figs.15 and 16 show the results of PBS under the river flow of U_c=0.8m/s. In this situation, every PBS drifts largely and closer to the bank, but the extent of drift doesn't seem to be fatal, yet. Indeed, although PBS has a large drift angle temporarily when steering, they all could pass through the narrow waterway between 2nd and 3rd waypoints by a relatively simple rudder control and with a smaller hull drift angle than that of the barge of TBS.

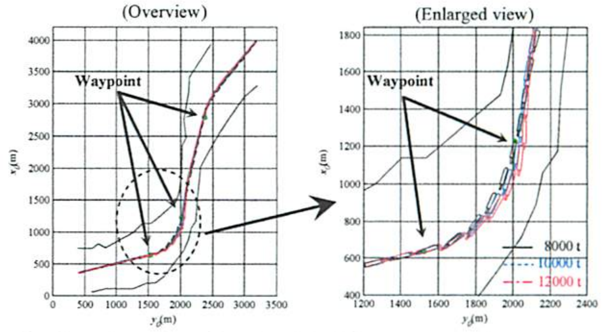

Fig.13 Trajectories of PBS with different sizes of the barge in U_c=0m/s

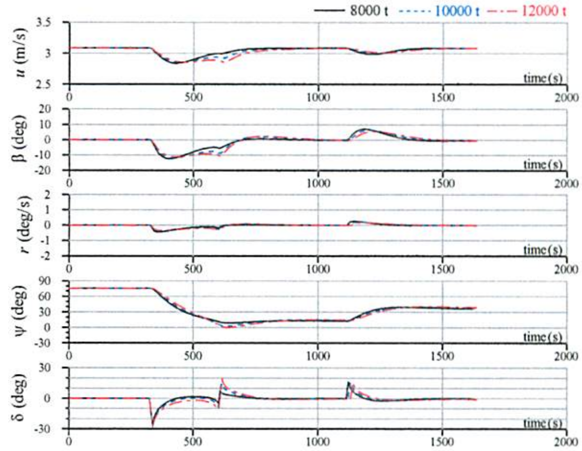

Fig.14 Time-series of manoeuvring behaviour of PBS with different sizes of the barge in U_c=0m/s

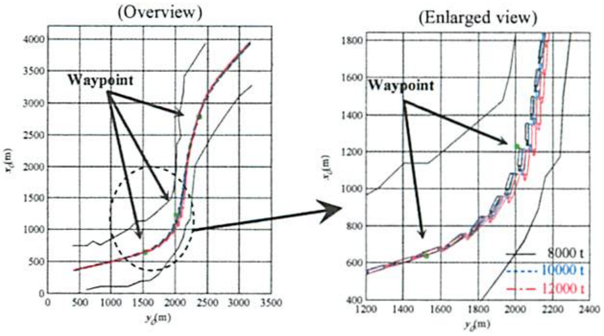

Fig.15 Trajectories of PBS with different sizes of the barge in U_c=0.8m/s

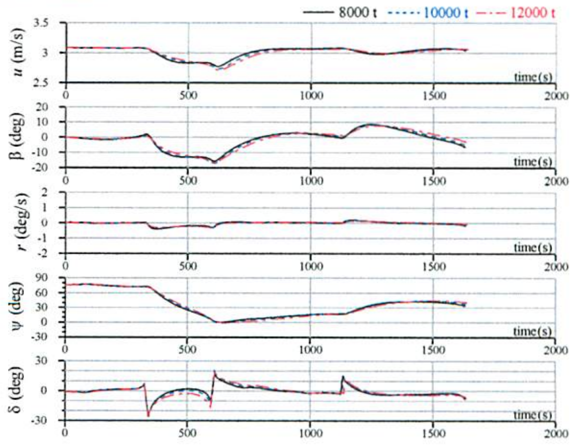

Fig.16 Time-series of manoeuvring behaviour of PBS with different sizes of the barge in U_c=0.8m/s

As conclusions, PBS would have good manoeuvrability enough for passing through such the S-shaped bend under the flow pressure without any assistant tug. The size of barge could increase more than the current size i.e. 8000t without fatal deterioration of manoeuvrability. But for more navigation safety, the first way point would be better to set farther upstream from the bend.

5. SIMULATION OF TBS AND PBS IN MEETING AND OVERTAKING SITUATIONS

5.1 MEETING SITUATION

Around Port of Samalinda, many ships are busy to sail and a lot of barges are also anchored in the middle of river. Since the area is always congested, the meeting and overtaking situations avoiding the anchored barges frequently occur. It seems that there is a high potential risk of near miss and collision accidents. As described in 2.1, MTSS has the function of avoidance and can decide an action plan for navigation safety. So such meeting and overtaking situations are assumed and the collision avoidance manoeuvre of TBS and PBS is discussed here.

Fig.17 shows the trajectories every 60 seconds of meeting situations such as [a] TBS (8000 t) – TBS (8000 t), [b] PBS (8000 t) - PBS (8000 t) and [c] PBS (12000 t)- PBS (12000 t) around an anchored 8000 t barge. The initial speed of each ship was at 4 knot. One of the meeting ships in red headed for going straight and another ship in blue ran diagonally in the opposite direction. The rudder control gains were set as P=D=1 for PBS and P=D=P_2=D_2=1 for TBS.

All three cases avoid collisions successfully. Compared with the cases of [a] and [b], TBS is largely diverted around the anchored barge, meanwhile PBS seems to avoid the barge more smoothly. Besides, from the enlarged view of the trajectory of TBS, the deviation of the heading angle between the tug and barge becomes larger when starting the avoiding behaviour and the towing barge seems to disturb the free and smooth manoeuvring. In consideration of the congested situation in the narrow river, it would be better for ship to pass near the obstruction with a smaller deviation like PBS. In other words, such a quick response ability would be advantage to the safety in an emergency case. The difference of the collision avoidance behaviour between [b] and [c] is small. Strictly speaking, since the development of manoeuvring motion of PBS (12000t) is slower than that of PBS (8000t) due to the large displacement, the deviation from the anchored barge slightly reduces. For more safety, the decision of avoidance should be made on the earlier stage as the size of barge is enlarged.

5.2 OVERTAKING SITUATION

Fig.18 shows the trajectories of overtaking situations where the ship in red went straight at 4 knot and another ship in blue tried to overcome her at 5 knot. The crossing situation occurred just around an anchored ship. The similar discussions can be made as the meeting situations. In all cases, the overtaken ship in red decided the right turn to avoid the ahead anchored barge. But it might have been better to take the left course because of the large space. So the algorithm of collision avoidance would be checked and improved if necessary for more realistic traffic flow.

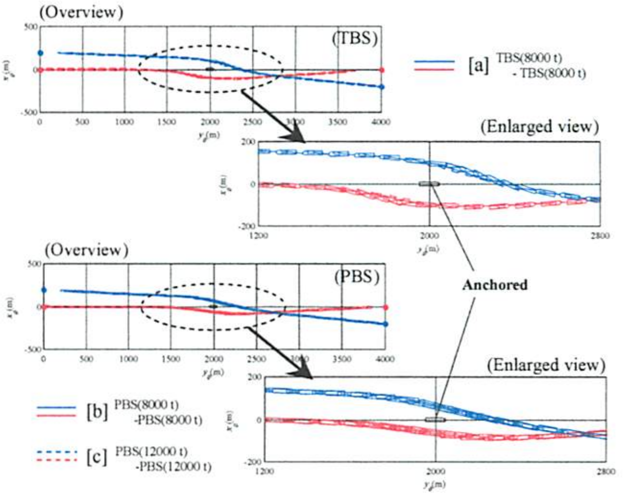

Fig.17Trajectories of collision avoidance manoeuvres in overtaking situations around an anchored barge

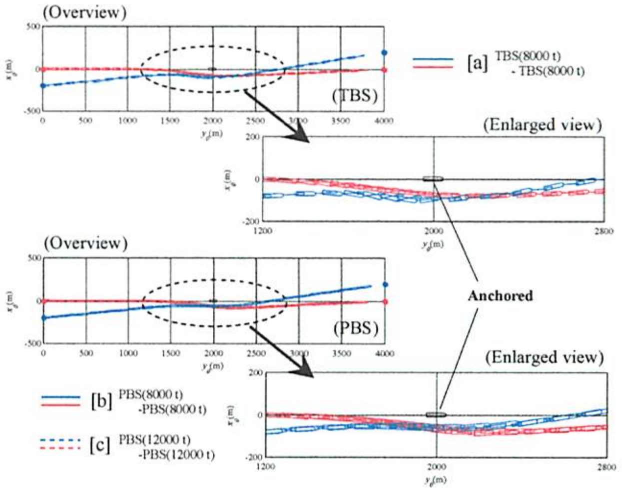

Fig.18 Trajectories of collision avoidance manoeuvres in overtaking situations around an anchored barge

6. CONCLUSION

The sophisticated manoeuvring mathematical model of ship so called MMG model was incorporated into Marine Traffic Simulator System. So MTSS became able to run simulation not only for macro marine traffic flows but also more detailed and complicated situations such as a towing condition or a drifting state in river flow with improving accuracy of manoeuvring behaviour.

This improved MTSS was used for the simulation of ships sailing in Mahakam River in Indonesia. Authors made rough computation models of a tug-barge system (TBS) which has been used for coal transport and conceptual pusher-barge systems (PBS) with different barge sizes. Their specifications were similar as those of the investigation report [8]. Compared with the manoeuvring behaviour between TBS and PBS when passing through the S-shape bend or in meeting /overtaking situations, it indicates PBS could become one of good options to improve the manoeuvring safety for Mahakam River service. The size of barge pushed by the pusher could become larger than the current size of barge without fatal deterioration of manoeuvrability.

This study is still in the 1st stage and more discussions should be made from various aspects. As one of them, traffic flow with a variety type of boats mixed in the river will be simulated for a long distance and a long period. The result such as near misses and collisions will be statistically analyzed for the assessment of navigation safety.

7. ACKNOWLEDGEMENTS

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