 SL, vol.9, no.1, pp.59-73, 2013

Group Preserving Scheme for Simulating Dynamic Ship Maneuvering Behaviors

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Abstract: In this paper, the group preserving scheme (GPS) is adopted to simulate the dynamic ship maneuvering behaviors. According to the mathematical model of the maneuvering ship motion, ship dynamic behaviors are affected by the ship hull resistance, rudder and propulsive propeller forces, and main engine induced force; therefore, the conventional approach uses the high order time integration to simulate the ship dynamic behaviors and results in the numerical instability. Due to the characteristics of the cone structure, Lie-algebra, and group property of the GPS, this research introduces the non-linear GPS to simulate the dynamic ship behaviors. Through the group weighting factor of the GPS, the non-linear parameters' behaviors can be observed and the numerical stability can be guaranteed. In addition, the second order of the GPS can ensure the accuracy of the high-order numerical method for simulating ship simulation behaviors and enhance the efficiency of the numerical calculation. Finally, results of the proposed approach are compared with the sea-trial data of a 278,000 DWT ESSO OSAKA ore & tanker [Crane (1979)] further validation.

Keywords: Group preserving scheme, numerical instability, ship dynamic behavior, ship maneuvering

1 Introduction

When the hydrodynamic forces during maneuvering are provided for each time step, no mathematical model is required. In such a case, only the equation of motion is used for simulations. Recently computer fluid dynamics (CFD) techniques have gradually made ship simulations possible; however, these simulation techniques cannot work to be satisfied due to the limited sea-trial data. In order to

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well describe the hydrodynamic forces for each time step, mathematical models are usually used. However, the expression is not so simple because there still exist non-linear terms and the interaction of ship hull and various wave motions. Consequently, the expressions of the hydrodynamic forces in the mathematical model are assumed to depend on velocity and acceleration components. That is a well-known "quasi-steady approach". In the figure 1 is the coordinate system for the simulation of ship maneuvering; the following equations of motion for four-degrees of freedom can be expressed as:

$$m(\dot{u} - vr) = X, \tag{1}$$

$$m(\dot{v} - ur) = Y, \tag{2}$$

$$I_{zz}\dot{r} = N, \tag{3}$$

$$I_{xx}\ddot{\psi} = K. \tag{4}$$

Here m represent the mass of a ship, I_{zz} is the inertia moment of yawing, I_{xx} is the inertia moment of rolling, X and Y denote the hydrodynamic forces in the x and y directions, and N and K denote the moments of the z and x directions acting on the gravity of the ship.

For the expression of these hydrodynamic forces and moment, some polynomial functions with acceleration and velocity components are used. The coefficients of them corresponding to hydrodynamic derivatives can be obtained from [Kobayashi (2002); Yoshimura (2005)]:

1. Captive model test such as oblique towing test (OTT), rotating arm test (RAT), circular motion test (CMT) and planar motion mechanism (PMM) test.

2. Numerical calculation.

3. Identification to the free-model tests or full- scale trials.

4. Database of hydrodynamic derivatives.

2 Mathematical MODEL

In 1976-1980, Japanese research group named Maneuvering Mathematical Modeling Group (MMG) proposed a mathematical model [Ogawa and Kasai (1978); Kose, Yumuro, and Yoshimura (1981)] which is call as MMG model.

2.1 Basic equation of motion

The mathematical model used in this study is shown as equations (1) to (3). These hydrodynamic forces and moments can be divided into the following components.

$$m(\dot{u} - vr) = X_H + X_P + X_R + X_W + X_C, \tag{5}$$

$$m(\dot{v} - ur) = Y_H + Y_P + X_R + Y_W + Y_C, \tag{6}$$

$$I_{zz}\ddot{\phi} = N_H + N_P + N_R + N_W + N_C, \tag{7}$$

$$I_{xx}\ddot{\phi} = K_H + K_P + K_R + K_W + K_C, \tag{8}$$

where subscripts H, P, R, W and C denote hull, propeller, rudder, wind and current, respectively. The equations (5-8) represent surge motion, sway motion, yawing motion and rolling motion, respectively.

2.2 Hydrodynamic forces and moment acting on the hull

As mentioned above, steady hydrodynamic forces with X_H and Y_H and moments with N_H and K_H are the functions of u, v, r, and β. Here r and β denote yawing rate and drift angle. In the total force model, these functions are described as the following polynomials using Taylor expansion, for example.

$$X_H = m_x\dot{u} + (m_x + X_{vr})vr + \frac{1}{2}\rho L^2V^2(X'_{vv}v'^2 + X'_{rr}v'r' + X'_{rr}r'^2 + X'_{vvvv}v'^4) + X(u). \tag{9}$$

$$Y_H = -m_y\dot{v} - m_xur + \frac{1}{2}\rho L^2V^2(Y'_\beta\beta' + Y'_rr' + Y'_{NL} + Y'_{\mathrm{Roll}}). \tag{10}$$

$$N_H = -J_{zz}\dot{r} + \frac{1}{2}\rho L^3V^2(N'_\beta\beta' + N'_rr' + N'_{NL} + N'_{\mathrm{Roll}}). \tag{11}$$

$$K_H = -J_{xx}\ddot{\phi} - N(\dot{\phi}) - mg\overline{GZ}(\phi) - Y_HZ_H. \tag{12}$$

These total force models can easily describe the steady hydrodynamic forces, and has been widely used. The coefficients in equations (9), (10), (11) and (12) are called hydrodynamic derivatives and can be obtained by some model tests [Kobayashi (2002)] using scaled model. These mathematical models can be usually applied for the simulation of the specified ship.

2.3 Hydrodynamic forces induced by propeller

The hydrodynamic forces induced by the propeller are expressed as follows:

$$2\pi J_{PP}\dot{n} = Q_E + Q_P. \tag{13}$$

$$X_P = (1-t_P)\rho n^2 D_P^4 K_T(J_P). \tag{14}$$

$$Q_P = 2\pi J_{PP}\dot{n} - \rho n^2 D_P^5 K_Q(J_P). \tag{15}$$

where t is thrust deduction factor, $\dot{n}$ is propeller revolution, D_P is propeller diameter, J_P is propeller advance ratio, J_{PP} is added polar moment of inertia of propeller, Q_P and Q_E are the moment of propeller and engine, and K_T and K_Q are the thrust coefficient and torque of propeller.

2.4 Hydrodynamic force and yaw moment induced by rudder

In order to considering the effect of hydrodynamic forces acting on hull, the forces caused by propeller and rudder are estimated using the following mathematical model, and are expressed as below:

$$X_R = -F_N \sin\delta, \tag{16}$$

$$Y_R = -(1+\alpha_H)F_N \cos\delta, \tag{17}$$

$$N_R = -(1+\alpha_H)x_R F_N \cos\delta, \tag{18}$$

$$K_R = (1+\alpha_H)z_R F_N \cos\delta, \tag{19}$$

where F_N is rudder normal force, δ is rudder angle, and x_R, α_H and z_R are the interactive coefficients between rudder and hull.

F_N is rudder normal force and can be described as following:

$$F_N = 0.5\rho \frac{6.13\lambda}{\lambda+2.25} A_R V_R^2 \sin\alpha_R, \tag{20}$$

$$\alpha_R = \delta - \gamma\beta_R^{'}, \tag{21}$$

$$\gamma = C_p \cdot C_s, \tag{22}$$

where λ is aspect ratio of rudder, A_R is rudder area, V_R is effective rudder inflow, α_R is effective rudder inflow angle, γ is flow-rectification coefficient, C_p is flow-rectification coefficient of propeller, and C_S is flow-rectification coefficient of ship form.

For describing the effect of propeller stream, the longitudinal and lateral inflow velocity of rudder can be described as the followings:

$$V_R = V(1-w_R)\sqrt{1+C_1 g(s)}, \tag{23}$$

$$g(s) = \frac{\eta k[2-(2-k)s]s}{(1-s)^2}, \tag{24}$$

$$\eta = D_p/H, \tag{25}$$

$$k = \frac{0.6(1-w_P}{1-w_R}, \tag{26}$$

$$C_P = \sqrt{\frac{(1-s)^2}{1+0.6\eta(2-1.4s)s}}, \tag{27}$$

$$s = 1 - \frac{u(1-w_P)}{nP}, \tag{28}$$

$$C_S = 0.45\beta_R^{'},\ \text{if}\ \beta_R^{'} \leq \frac{0.5}{0.45},$$

$$\text{or}\ C_S = 0.5,\ \text{if}\ \beta_R^{'} > \frac{0.5}{0.45}, \tag{29}$$

$$\beta_R^{'} = \beta - 2x^{'}r^{'}, \tag{30}$$

where H is rudder height, w_R is effective rudder wake fraction, s is slip ratio, P is propeller pitch.

3 Group Preserving Scheme

The group-preserving scheme [Liu (2001); Chen, Liu, and Chang (2007)] is a scheme that can preserve the internal symmetry group of the considered system. Although previously we do not know what kind symmetry group of the general nonlinear dynamical systems is, yet Liu (2001) has embedded them into the augmented dynamical systems, which concern with not only the evolutions of the state variable itself but also with the evolution of its magnitude. That is, for the general dynamical system of n ordinary differential equations:

$$\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x},t), \quad \mathbf{x} \in \mathbf{R}, t \in \mathbf{R}, \tag{31}$$

We can embed it into the following $(n+1)$-dimensional augmented dynamical system:

$$\frac{d}{dt}\begin{bmatrix} \mathbf{x} \\ ||\mathbf{x}|| \end{bmatrix} = \begin{bmatrix} \mathbf{0}_{n\times n} & \frac{\mathbf{f}(\mathbf{x},t)}{||\mathbf{X}||} \\ \frac{\mathbf{f}^T(\mathbf{x},t)}{||\mathbf{X}||} & 0 \end{bmatrix} = \begin{bmatrix} \mathbf{x} \\ ||\mathbf{x}|| \end{bmatrix} \tag{32}$$

Consequently, we have an $(n+1)$-dimensional augmented system:

$$\dot{\mathbf{X}} = \mathbf{A}\mathbf{X} \tag{33}$$

With a constraint of equation (33), where

$$\mathbf{A} = \begin{bmatrix} \mathbf{0}_{n\times n} & \frac{\mathbf{f}(\mathbf{x},t)}{||\mathbf{X}||} \\ \frac{\mathbf{f}^T(\mathbf{x},t)}{||\mathbf{X}||} & 0 \end{bmatrix} \tag{34}$$

Satisfying

$$\mathbf{A}^T\mathbf{g} + \mathbf{g}\mathbf{A} = \mathbf{0} \tag{35}$$

Remarkably, the original n-dimensional dynamical system of equation (31) in E^n can be embedded naturally into an augmented $(n+1)$-dimensional dynamical system of equation (33) in $\mathbf{M}^{n+1}$. Although the dimension of the new system is raised by one, it shows that the new system has the advantage of devising group-preserving numerical scheme as follows [Liu (2001)]:

$$\mathbf{X}_{\ell+1} = \mathbf{G}(\ell)\mathbf{X}_{\ell}, \tag{36}$$

where $\mathbf{X}_{\ell+1}$ denotes the numerical value of $\mathbf{X}$ at the discrete time t_ℓ, and $\mathbf{G}(\ell) \in SO_0(n,1)$ is the group value at time t_ℓ.

Inserting the above Cay $[\tau\mathbf{A}(\ell)]$ for $\mathbf{G}(\ell)$ into equation (36) and ranking its first row, we obtain

$$\mathbf{x}_{\ell+1} = \mathbf{x}_\ell + hw(\ell)\mathbf{f}_\ell \tag{37}$$

$$w(\ell) = \frac{||\mathbf{x}_\ell||^2 + \tau\mathbf{f}_\ell\cdot\mathbf{x}_\ell}{||\mathbf{x}_\ell||^2 + \tau^2||\mathbf{f}_\ell||^2} \tag{38}$$

Where is called a weighting factor. In the above, x_ℓ denotes the numerical value of $\mathbf{x}$ at the discrete time t_ℓ, τ is one half of the time increment, i.e., $\tau = h/2$, and more precisely, f_ℓ is $f(x_\ell, t_\ell)$.

4 Numerical Examples

According to the above-mentioned MMG model, maneuvering ship motions can be predicted by the computer simulation. The principal particulars are listed in Table 1. Hydrodynamic derivatives and coefficients for the simulation are listed in Table 2. According to turning circle test, simulated ship motions, ψ, r, the non-dimensional velocity ratio ,and ship trajectory, under turning right rudder 35° are

Table 1: General Data for a Sample Ship

Length between perpendiculars, L, m	343
Breadth molded, B, m	53
Draft in full load, T, m	21.76
Block coefficient	0.831
Displacement, metric tons	27313.5
Longitudinal position of center of gravity, xcg, m	10.3
Movable rudder area, AR, m^2	119.817
Rudder span, Sp, m	13.85
Engine type:	Diesel
Maxim continuous rating of engine MCR, RPM	82
Nominal continuous rating of engine NCR, RPM	81

Table 2: Hydrodynamic Coefficients [Chu and Tseng (1988)]

Symbol	*Value*	*Symbol*	*Value*	*Symbol*	*Value*
X'_{vv}	-0.001276	$Y'_{\beta\gamma}$	0.022335	N'_{rr}	-0.000976
X'_{rr}	0.0003	Y'_{γ}	0.0045843	N'_{β}	0.0094447
X'_{vvvv}	0.045241	$Y'_{\beta\beta}$	0.02255	N'_{r}	-0.0036063
		$Y'_{\gamma\gamma}$	-0.0022275	$N'_{rr\beta}$	-0.005014

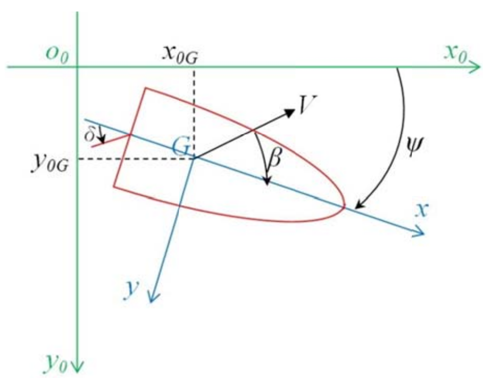

Figure 1: Co-ordinate system

shown in figs. 2-5. In additional, ship motions, ψ, r, the non-dimensional velocity ratio ,and ship trajectory, under turning left rudder 35° are shown in figs. 6-9.

In order to further test maneuvering stability, we compute heading change and yawing rate by the zig-zag test. Under rudder at 10/-10 and 20/-20 by zig-zag test, the rudder angle, yawing rate and heading change of ESSO OSAKA are shown in figs. 10-13. In summary, the method presented is a more effective and convenient approach to simulate maneuvering ship motion problems.

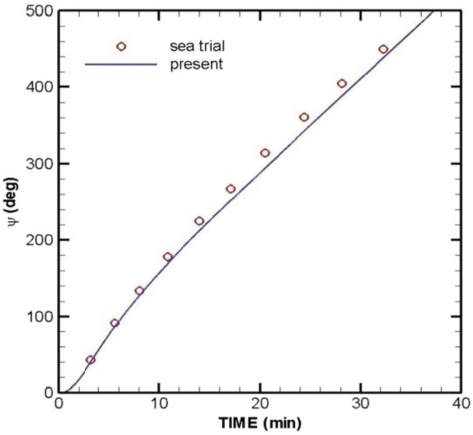

Figure 2: Comparisons of numerical results and sea trial data of ESSO OSAKO for the yawing varying with time at right rudder 35° condition

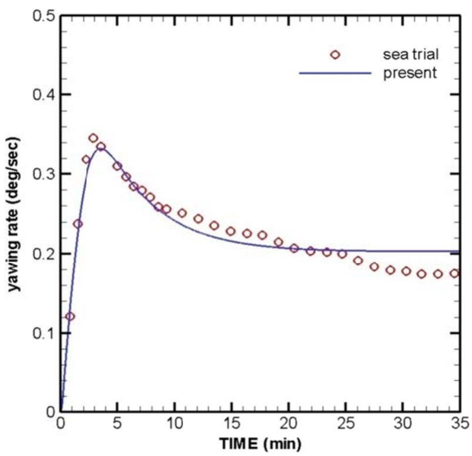

Figure 3: Comparisons of numerical results and sea trial data of ESSO OSAKO for the yawing rate varying with time at right rudder 35° condition

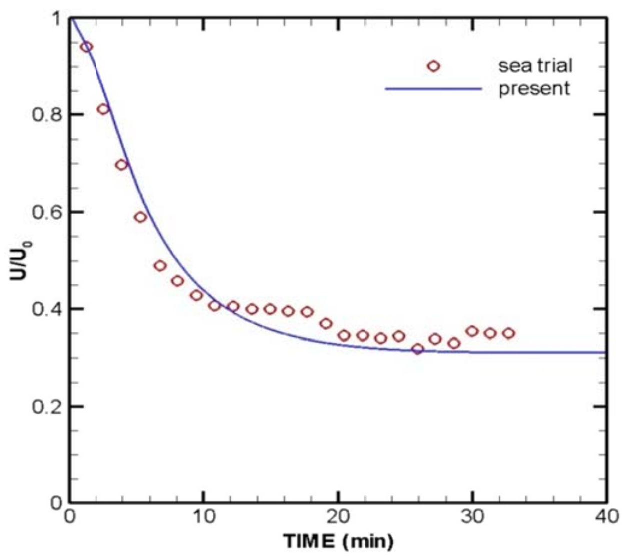

Figure 4: Comparisons of numerical results and sea trial data of ESSO OSAKO for the non-dimensional velocity ratio varying with time at right rudder 35° condition

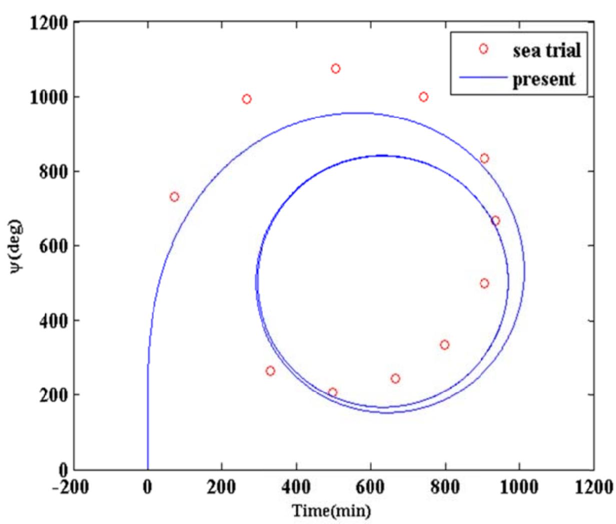

Figure 5: Comparisons of numerical results and sea trial data of ESSO OSAKO for the simulated turning circle track at right rudder 35° condition

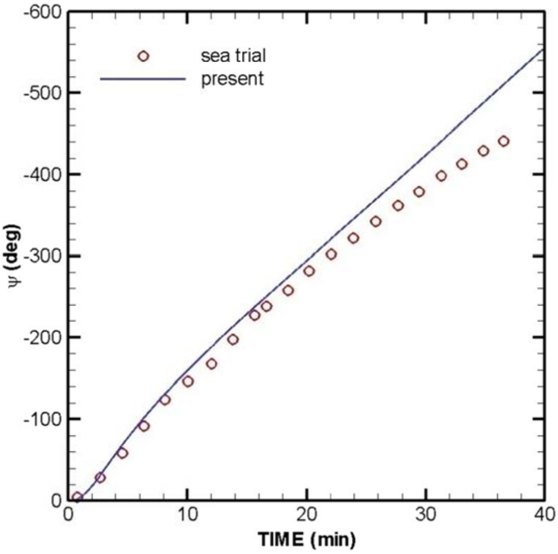

Figure 6: Comparisons of numerical results and sea trial data of ESSO OSAKO for the rudder angle varying with time at left rudder 35° condition

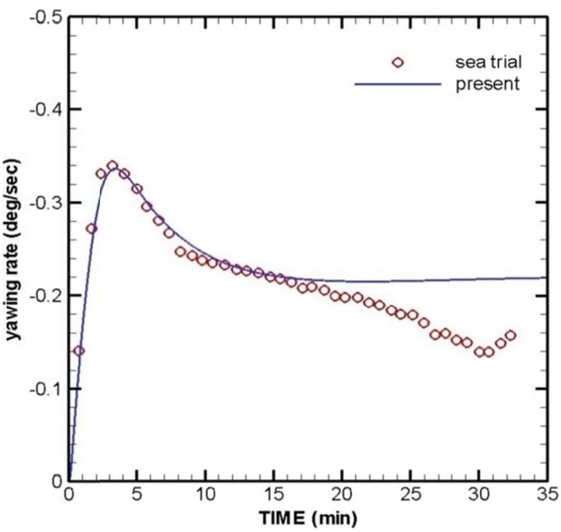

Figure 7: Comparisons of numerical results and sea trial data of ESSO OSAKO for the yawing angle velocity varying with time at left rudder 35° condition

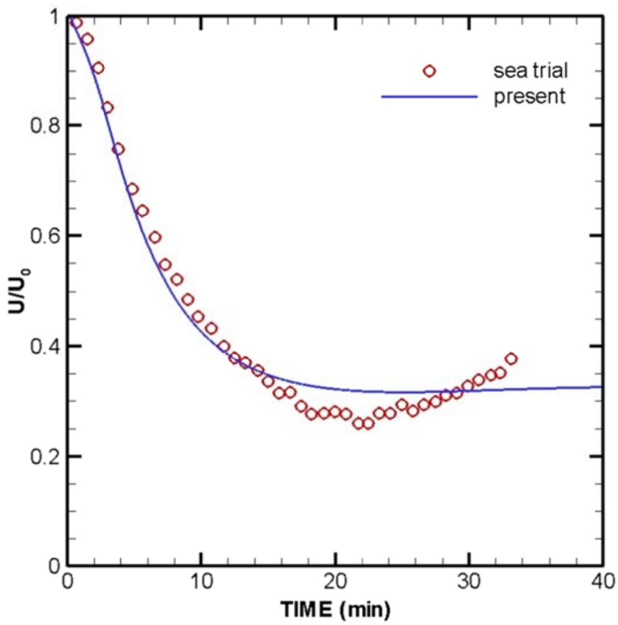

Figure 8: Comparisons of numerical results and sea trial data of ESSO OSAKO for the non-dimensional velocity ration varying with time at left rudder 35° condition

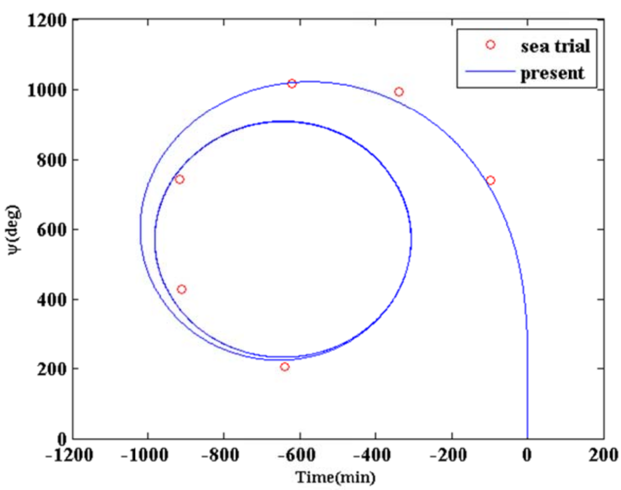

Figure 9: Comparisons of numerical results and sea trial data of ESSO OSAKO for the simulated turning circle track at left rudder 35° condition

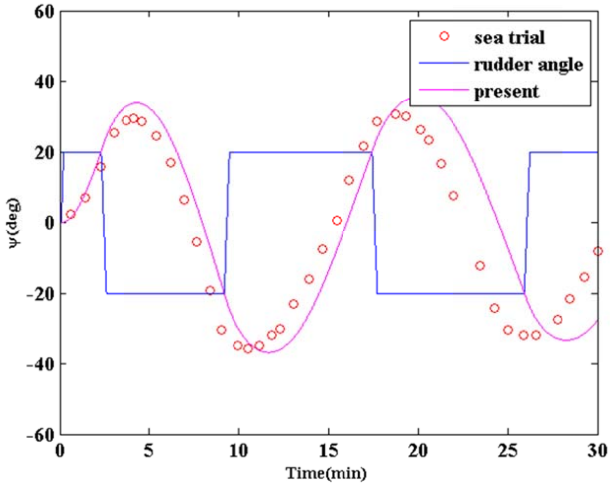

Figure 10: Comparisons of numerical results and sea trial data of ESSO OSAKO for the heading change varying with time at 20/20 zig-zag test

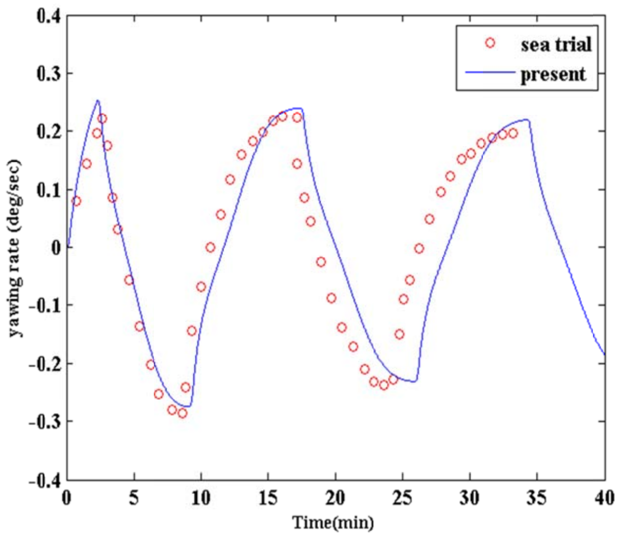

Figure 11: Comparisons of numerical results and sea trial data of ESSO OSAKO for the yawing rate varying with time at 20/20 zig-zag test

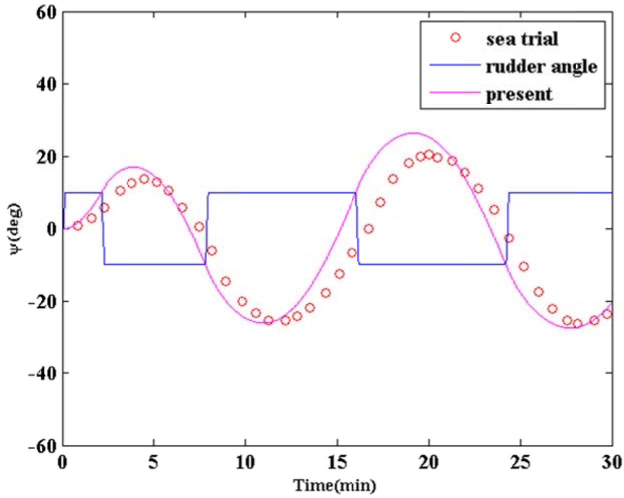

Figure 12: Comparisons of numerical results and sea trial data of ESSO OSAKO for the heading change varying with time at 10/10 zig-zag test

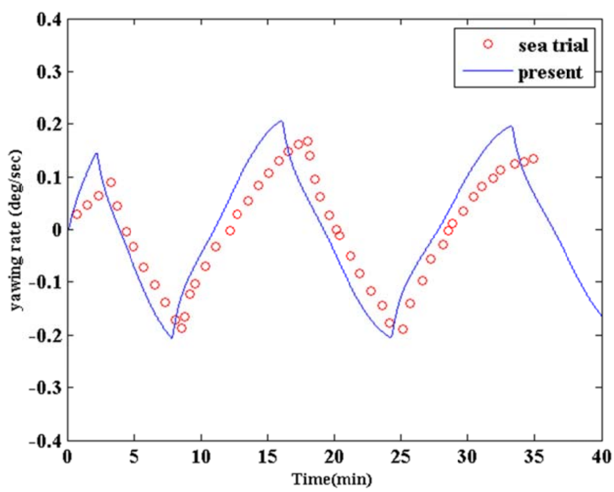

Figure 13: Comparisons of numerical results and sea trial data of ESSO OSAKO for the yawing rate varying with time at 10/10 zig-zag test

5 Conclusions

In this paper, we have successfully applied the GPS to simulate ship maneuvering behaviors. Since the ship dynamic behaviors are affected by those non-linear forces such as the ship hull resistance, rudder and propulsive propeller forces and induced engine force, the non-linear GPS is adopted to simulate the dynamic ship behaviors and ensure the numerical stability. Through the group weighting factor of the GPS, the non-linear parameters' behaviors can be observed and the numerical instability can be overcome. In addition, the second order of the GPS can ensure the accuracy of the high-order numerical method for simulating ship simulation behaviors. Finally, results of the proposed approach are compared with the sea-trial data of turning circle test in a 278,000 DWT ESSO OSAKA ore & tanker for further validation.

Acknowledgement: The authors would like to express his thanks to the National Science Council, Taiwan for their financial support under contract number: NSC-102-2218-E-019-001 and NSC-99-2221-E-019-053-MY3.

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