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(Citation)
Journal of maritime researches,5:1-13

(Issue Date)
2015-06

(Resource Type)
departmental bulletin paper

(Version)
Version of Record

(JaLCDOI)
https://doi.org/10.24546/81009083

(URL)
https://hdl.handle.net/20.500.14094/81009083

Journal of Maritime Researches Vol. 5, March 2015: 1-13.

NOVEL IDENTIFICATION METHOD OF MANEUVERABILITY INDICES CONCERNING DRIFT MOTION BASED ON SUCCESSIVE DATA ASSIMILATION

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ABSTRACT

Novel identification method of maneuverability indices concerning drift motion is proposed in this study. This method is based on successive data assimilation which is a new methodology combining the idea of the time series analysis and the computational simulation. In this methodology, the prediction with the computational simulation in the framework of the general state-space modeling procedure is improved by using the observation data with the full scale or model experiment. In this study, the self-organizing state-space (SOSS) modeling procedure is specifically applied to identify unknown parameters that is the maneuverability indices concerning the drift motion. The Monte Carlo filter is adopted to perform the state estimation in SOSS modeling. In order to verify the proposed procedure, numerical experiments were carried out. From the results, it can be confirmed that the maneuverability indices concerning the drift motion are identified well.

Keywords: maneuverability, self-organizing state-space modeling procedure, Monte Carlo filter, two dimensional observation model, successive data assimilation

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1. INTRODUCTION

It is very important for ship officers to understand the maneuverability of their operating ship from the viewpoint of maintaining ship safety. In general, the tactical diameter obtained from a turning test, overshoot angle and maneuverability indices concerning yaw motion, which was proposed by Nomoto et. al. (1956), obtained from a zig–zag test are used as an index to evaluate the maneuverability.

In these evaluation indices, maneuverability indices concerning yaw motion are practical and useful for officers. It is well known that there are unknown parameters in the Nomoto model which is a first order approximation of a maneuvering response model. Nomoto et. al. (1956), Iseki and Ohtsu (1998), Terada and Kitagawa (2009), Hane (2014) and so on have proposed a practicable parameter identification method

so far. Among these methods, the method of Terada and Kitagawa (2009) and Hane (2014) can identify parameters by using ordinary navigation data. As mentioned before, the data of the zig–zag test is generally used for the parameter identification. Therefore, the point concerning the unconstrained data is one of the major advantages of their method. Especially, the method of Hane (2014) can also identify maneuverability indices concerning drift motion and is excellent, although the model is modified from the original Nomoto model. However, the Hane's method has a problem in which it is required to do the iteration calculation due to the parameter identification.

On the other hand, the method of Terada and Kitagawa (2009), which is based on successive data assimilation (Nakamura et. al., 2005), has features in which the algorithm is completely successive and is not required to do the iteration calculation. These are very important for a robust identification, since a

Ship's speed and a external disturbance can change under navigation. Thus, by devising a model of the maneuvering motion, it is considered that it is possible to identify maneuverability indices concerning drift motion as well as Hane (2014) even if it uses the method of Terada and Kitagawa (2009).

From this background, we attempt to identify maneuverability indices concerning drift motion based on successive data assimilation. If maneuverability indices concerning drift motion can be identified, then it is possible to estimate the trajectory of the ship. Therefore, we verify the proposed method by using the data of the ship's trajectory. The data of the trajectory is reproduced by MMG model (Yasukawa and Yoshimura, 2014), which was developed in Japan, and subjected to numerical experiments. The results are reported in detail.

2. SIMULATION MODEL ON MANEUVERING MOTION

2.1 Maneuvering response model

Successive data assimilation is equivalent to a state-space modeling procedure in the field of statistical science, when a discrete model for numerical calculation on the physical process are dealt with a system model in the state-space model. Therefore, we firstly considered the discrete model for numerical calculation on maneuvering motion. And we call this model the simulation model.

Consider that the following models in which a white noise sequence is added to Nomoto's models.

$$T_r\dot{r}(t)+r(t)=K_r\delta(t)+v_r(t) \tag{1}$$

$$T_\beta\dot{\beta}(t)+\beta(t)=K_\beta\delta(t)+v_\beta(t) \tag{2}$$

where, T is an index of responsiveness to the helm, $r(t)$ is a yaw rate, $\beta(t)$ is a drift angle, K is an index of turning ability, $\delta(t)$ is a rudder angle and $v(t)$ is a gaussian white noise sequence with a mean of 0 and a variance of τ^2. Additionally, the notation $(\cdot)$ indicates a first order differential operator with respect to time, and the suffixes r and β indicate variables concerning the yaw rate r and the drift angle β, respectively. As a time step is Δt, and by using analytic solutions, Equation (1) and (2) can be represented as follows.

$$r(t+\Delta t)=\exp\left[-\frac{\Delta t}{T_r}\right]r(t)-\left(\exp\left[-\frac{\Delta t}{T_r}\right]-1\right)K_r\delta(t)+v_r(t+\Delta t) \tag{3}$$

$$\beta(t+\Delta t)=\exp\left[-\frac{\Delta t}{T_\beta}\right]\beta(t)-\left(\exp\left[-\frac{\Delta t}{T_\beta}\right]-1\right)K_\beta\delta(t)+v_\beta(t+\Delta t) \tag{4}$$

where,

$$v(t+\Delta t)=\int_t^{t+\Delta t}\exp\left[-\frac{1}{T}(t+\Delta t+t')\right]v(t')dt' \tag{5}$$

$$E\left[v(t+\Delta t)\right]=0 \tag{6}$$

$$E\left[v(t+\Delta t)^2\right]=\frac{T}{2}\left(1-\exp\left[-\frac{\Delta t}{T}\right]\right)\tau^2\cong\Delta t\tau^2 \tag{7}$$

Here, note that the suffixes r and β are omitted for simplicity of explanation.

2.2 Time update of motions

Consider a ship fixed coordinate system o−xy and an earth fixed coordinate system O-XY as Fig.1. Then a time update concerning the position (x, y) and the course ψ can be expressed as follows.

$$x(t+\Delta t)=x(t)+\Delta t\left[V_x(t)\cos\psi(t)-V_y(t)\sin\psi(t)\right] \tag{8}$$

$$y(t+\Delta t)=y(t)+\Delta t\left[V_x(t)\sin\psi(t)+V_y(t)\cos\psi(t)\right] \tag{9}$$

$$\psi(t+\Delta t)=\psi(t)+\Delta t r(t) \tag{10}$$

where, $V_x(t)$ and $V_y(t)$ respectively indicate a ship speed concerning x axis and y axis and are calculated from following formula.

$$V_x(t+\Delta t) = V_x(t) + v_{Vx}(t+\Delta t) \tag{11}$$

$$V_y(t) = -V_x(t)\tan\beta(t) \tag{12}$$

For the sake of simplicity, the time update of $Vx(t)$ is treated as a random walk model which is a kind of a statistical model. Here, $v_{Vx}(t+\Delta t)$ is a gaussian white noise sequence with a mean of 0 and a variance of τ^2_{Vx}.

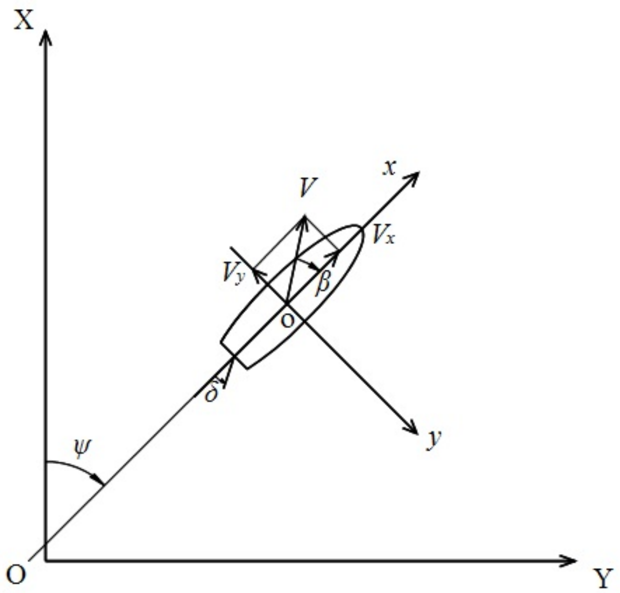

Fig. 1 Coordinate system

2.3 Simulation model

The simulation model used in this study is Equation 3, 3 and from 8 to 12. By using these equations, it is possible to estimate the turning motion of a ship. In these equations, the notation is changed for simplicity from $t + \Delta t$ to n, and from t to $n - 1$. And these equations can be expressed by vector form as follows. Here, note that the rudder angle δ(n) uses the measured time series data.

$$X(n) = f\left(X(n-1), v(n)\right) \tag{13}$$

Where, $X(n) = [x(n), y(n), Vx(n), \beta(n), \psi(n), r(n)]^T$ corresponds to a state vector in a general state-space model, and $v(n) = [0, 0, v_{Vx}(n), v_\beta(n), 0, vr(n)]^T$ corresponds to a system noise vector in a general state-space model. Furthermore, $f(*)$ indicates a nonlinear operator consisting of $X(n)$ and $v(n)$, while the notation 'T' means a transpose of vectors or matrix . Note that this is different from the maneuverability index $T*$.

3. SUCCESSIVE DATA ASSIMILATION

As mentioned before, we described that successive data assimilation is equivalent to a state-space modeling procedure, and introduced the simulation model expressed by

Equation 13 which is the system model in the state–space model. Therefore, now we introduce the observation model in the general state– space model which corresponds to the state vector. Suppose that a ship speed V_{obs} and a yaw rate r_{obs} are able to observe, then the observation model can be expressed by the following equation.

$$V_{\text{obs}}(n) = \sqrt{V_x(n)^2 + \left(-V_y(n)\tan\beta(n)\right)^2} + w_V(n) \tag{14}$$

$$r_{\text{obs}}(n) = r(n) + w_r(n) \tag{15}$$

These equations can be expressed by vector form as follows.

$$\boldsymbol{y}(n) = h\left(X(n), w(n)\right) \tag{16}$$

Where, $\boldsymbol{y}(n) = [V_{\text{obs}}(n), r_{\text{obs}}(n)]^T$ and $h(*)$ indicates a nonlinear operator composed the $X(n)$ and the $w(n)$. And $w(n) = [w_V(n), w_r(n)]^T \sim N(0, \Sigma)$ is an observation noise vector with mean 0 and variance–covariance matrix $\Sigma = \text{diag}(\sigma^2{}_V, \sigma^2{}_r)$. Note that the observation noise vector has the following inverse function.

$$w(n) = g\left(\boldsymbol{y}(n), X(n)\right) \tag{17}$$

Therefore, the general state–space model being introduced, and which was summarized above, is composed of Equation 13 and 16.

On the other hand, our purpose is to identify the maneuverability indices. So, we consider that the maneuverability indices are treated as time varying parameters for the effective parameter identification in the state–space modeling, although they are constant with time. As the results indicate, we can simultaneously perform the state estimation, such as the ship speed, the yaw rate, and the parameter identification. For simplicity, suppose that parameters can be expressed by the following random walk model.

$$\theta(n) = \theta(n-1) + \varepsilon(n) \tag{18}$$

Here,

$$\theta(n) = \Big[K_\beta(n), T_\beta, K_r(n), T_r, \log\tau^2{}_{K\beta}(n), \log\tau^2{}_{Kr}(n),$$
$$\log\tau^2{}_{Vx}(n), \log\tau^2{}_\beta(n), \log\tau^2{}_r(n), \log\sigma^2{}_V(n), \log\sigma^2{}_r(n)\Big]^T$$

And also, $\varepsilon(n) \sim N(0, \Sigma_\theta(n))$ is a gaussian white noise sequence with a mean of 0, variance–covariance matrix $\Sigma_\theta(n)$. Here, $\Sigma_\theta(n)$ can be expressed by

$$\Sigma_\theta(n) = diag\left(\tau^2{}_{K\beta}(n), 0, \tau^2{}_{Kr}(n), 0, \eta^2{}_{K\beta}, \eta^2{}_{Kr}, \eta^2{}_{Vx}, \eta^2{}_\beta, \eta^2{}_r, \eta^2{}_{\sigma V}, \eta^2{}_{\sigma r}\right).$$

In this case, $\eta^2{}_{K\beta}$, $\eta^2{}_{Kr}$, $\eta^2{}_{Vx}$, $\eta^2{}_\beta$, $\eta^2{}_r$, $\eta^2{}_{\sigma V}$ and$\eta^2{}_{\sigma r}$ are a hyper-parameter that controls the trade-off between the good fit to the data and the smoothness of the parameter change in the model. Consider that it is including the parameter vector $\theta(n)$ in the state vector $X(n)$. Then, we can define the following extended state vector $X(n)$ and noise vector $u(n)$,

$$Z(n) = \left[X(n)^T, \theta(n)^T\right]^T \tag{19}$$

$$u(n) = \left[v(n)^T, \varepsilon(n)^T \right]^T . \tag{20}$$

From Equation 20, we can extend the generalized state space model into the following self-organizing state space (SOSS) model (Kitagawa, 1998):

$$\begin{aligned} Z(n) &= F\left(Z(n-1), u(n)\right) \\ \boldsymbol{y}(n) &= H\left(Z(n), w(n)\right) \end{aligned} \tag{21}$$

4. MONTE CARLO FILTER

To implement the state estimation of Equation 21, we apply a Monte Carlo filter (MCF) proposed by Kitagawa (1996) which is effective for the nonlinear non-Gaussian state-space modeling. It should be noted that in this subsection, the symbol (n) that is a meaning of variable for the time used in Equation 21 is expressed by subscript symbol, for simple expression of equations. In this method, each probability density function that is the predictor $p(z_n|Y_{n-1})$ and the filter $p(z_n|Y_n)$; where Y_n is the set of observations $y_1,\ldots, y_N$, is approximated by J particles, which can be regarded as independent realizations from that distribution. According to Kitagawa (1996), it can be shown that these particles can be recursively given by the following Monte Carlo filter algorithm:

[Step 1]

Generate the 17 dimensional random number $f_0^{(j)} \sim p_0(z)$ for $j = 1 \sim J$.

[Step 2]

Repeat the following steps for $n = 1 \sim N$.

1. Generate the 17 dimensional random number $v_n^{(j)} \sim q(v)$ for $j = 1 \sim J$.
2. Compute the following equation:

$$p_n^{(j)} = F\left(f_{n-1}^{(j)}, v_n^{(j)}\right) \tag{22}$$

3. Compute the likelihood function as follows:

$$\alpha_n^{(j)} = \frac{1}{2\pi\left|\Sigma_w\right|} \exp\left[-\frac{1}{2} g\left(\boldsymbol{y}_n, p_n^{(j)}\right)^T \Sigma_w^{-1} g\left(\boldsymbol{y}_n, p_n^{(j)}\right) \right] \tag{23}$$

where Σ_w is the variance co-variance matrix of the observation noise.

4. Generate $f_n^{(j)}$ according the following probability for $j = 1 \sim J$ by the resampling of $p_n^{(1)} \sim p_n^{(J)}$.

$$\Pr\left(f_n^{(j)} = p_n^{(j)} \right) = \frac{\alpha_n^{(j)}}{\alpha_n^{(1)} + \cdots + \alpha_n^{(J)}} . \tag{24}$$

5. NUMERICAL EXPERIMENTS

In order to examine the effectiveness of the proposed procedure, numerical experiments are carried out. The sample ship is the training ship ”Fukae–Maru” belonging to the Kobe university. Table 1 shows the principal dimensions of the Fukae-Maru. The time series for the parameter identification are reproduced based on the MMG model. In this case, various coefficients in the MMG model are given based on Society of Naval Architects of Japan (1981). In order to understand the characteristic of the maneuvering motion reproduced by the MMG model, the zig–zag trial is simulated under an initial speed 15 knots and a rudder angle of 35 degrees. The reproduced time series data are shown in fig. 2. In this figure, the time interval is 1.0(sec), and the thin line indicates the ship course and the thick line indicates the rudder angle, respectively. Table 2 shows the estimated maneuverability indices concerning the yaw based on Nomoto's method. As shown in this table, the index T_r is 4.02(sec) and the index K_r is 0.137(1/sec). In this study, we treat these values as the true value of the maneuverability indices concerning the yaw.

Table 1 Principal particulars of Fukae-Maru

Length (P.P)	45.0	m
Breadth (M_{LD})	10.0	m
Draught (M_{LD})	3.20	m
Block Coeff.	0.53	

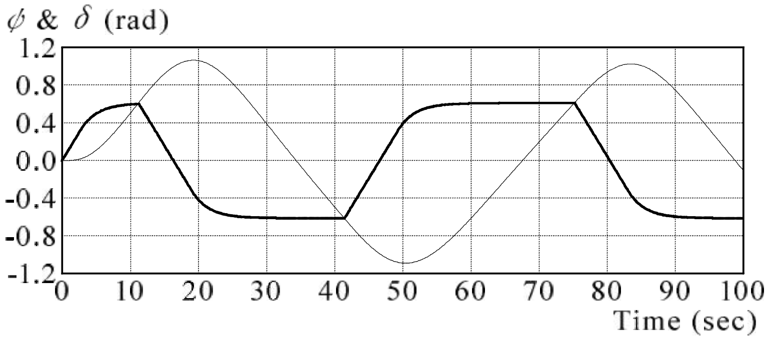

Fig. 2 Time history of ship course and rudder angle of zig-zag trial test under rudder angle = 35 degrees

Table 2 Maneuverability indices obtained from the traditional graphical method

Index T_r	4.02	sec
Index K_r	0.137	1/sec

Fig. 3 and Fig. 4 show the data of the turning test obtained from numerical simulation. Fig.3 is the result of starboard side 35 degrees turning test, and Fig.4 is the result of port side 35 degrees turning test, respectively. In these figures, the left hand side's figure shows the trajectory of the ship. And also, as to the right hand side respectively shows the resultant ship speed V, the yaw rate r and the drift angle β from the top to bottom. As for the feature of the turning motion, a tactical diameter of the starboard side turning is larger than one of the port side turning. In the successive data assimilation, as mentioned before, we use the resultant ship speed V and the yaw rate r as the observation data.

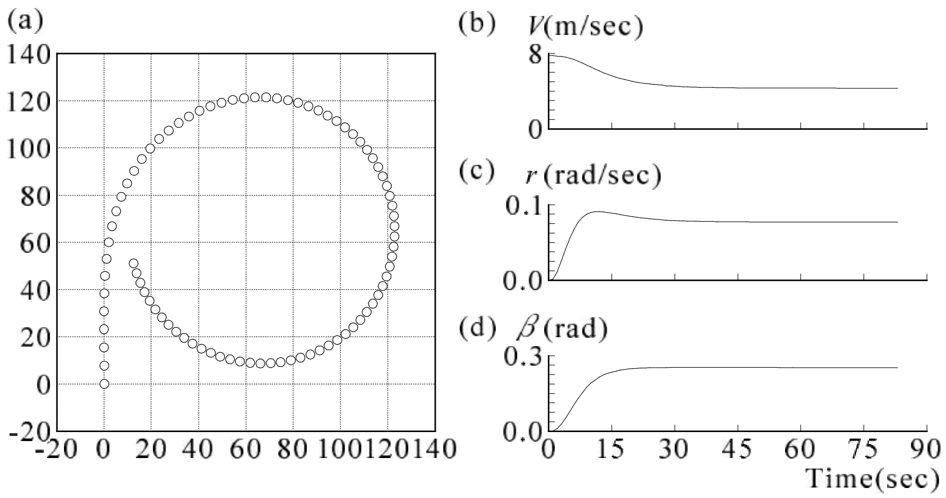

Fig. 3 Data of starboard side turning test obtained from numerical simulation

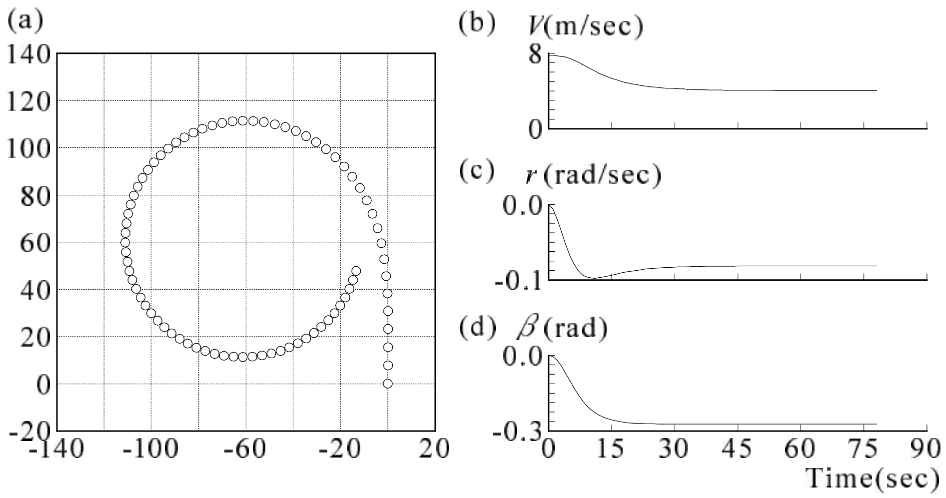

Fig. 4 Data of port side turning test obtained from numerical simulation

6. RESULTS AND DISCUSSIONS

Results of the state estimation and the parameter identification based on the proposed method are shown in Fig. 5 and Fig. 6, respectively. Fig. 5 is the result of the starboard side turning, and Fig. 6 is the result of the port side turning. In these figures, (a) is the trajectory of the ship (X,Y), (b) is the deviation of the position against the true value, (c) is the ship speed V_x concerning the x axis, (d) is the ship speed V_y concerning the y axis, (e) is the yaw rate r, (g) is the index of responsiveness to the helm T concerning the yaw and (f) is the index of turning ability K concerning the yaw. In these figures, the symbol "◦" indicates the true value and the straight line indicates the estimated one. Additionally, in figure (b) the thin line indicates the result of x direction and the thick line indicates the result of y direction, respectively. Note that we selected the expectation of the filter distribution as estimated values. It can be seen that the estimated values by using the ship speed and the yaw rate are in good agreement with the true values. Moreover, it is notable that the ship speed V_y of Y axis can estimate well, even using the Nomoto model as the maneuvering motion model.

Fig. 7 and Fig. 8 show the results of the parameter identification of the maneuverability indices concerning the drift motion, respectively. Fig. 7 is the result of the starboard side turning, and Fig. 8 is the result of the port side turning. In these figures, the thick line indicates the index of responsiveness to the helm T and the thin line indicates the the index of turning ability K. It can be seen that as to the index T, which there are 5.15(sec) in the starboard side turning and 3.97(sec) in the port side turning is the constant with time, and as to the index K, which there are 0.126(1/sec) in the starboard side turning and 0.133(1/sec) in the port side turning is constant with time except for the part of transient response. It is considered that the results are reasonable as well as the results concerning the yaw, since the rudder force is generally different depending on the turning motion of the starboard side or the port side. Therefore, we consider that the proposed method can identify the maneuverability indices concerning the drift motion, although the true values are unknown.

From this discussion, it can be considered that the proposed method is practical, since the identification of the maneuverability indices concerning the yaw and the drift angle and the state estimation of the trajectory of ship, the ship speed and so on can be performed simultaneously by using the ship resultant speed V and the yaw rate r observed under the turning test. Therefore, it can be considered that the proposed method can be utilized as a powerful tool to understand the feature of the maneuvering motion of the ship for ship officers.

7. CONCLUSIONS

In this study, the novel method for the parameter identification on the maneuverability indices concerning the drift motion is proposed based on successive data assimilation. As to the feature of this method, it is that the identification of the maneuverability indices concerning the drift motion are simultaneously performed with the estimation of the maneuvering motion and the identification of the maneuverability indices concerning the yaw. In order to examine the effectiveness of the proposed method, numerical experiments by using the training ship the ”Fukae-Maru” belonging to the Kobe university were carried out. The findings are summarized as follows:

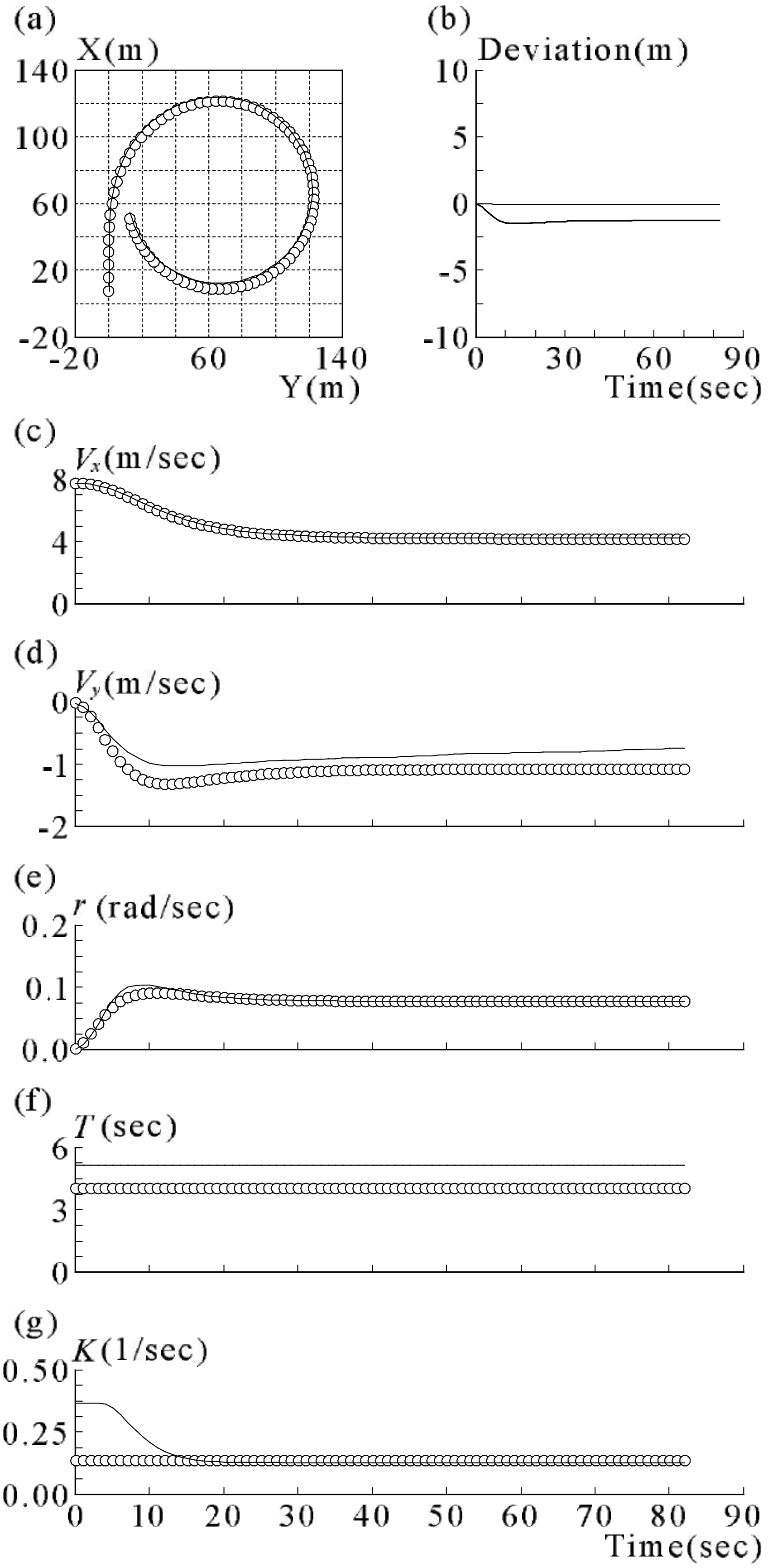

Fig. 5 Comparison of true values and estimated values under starboard side turning test

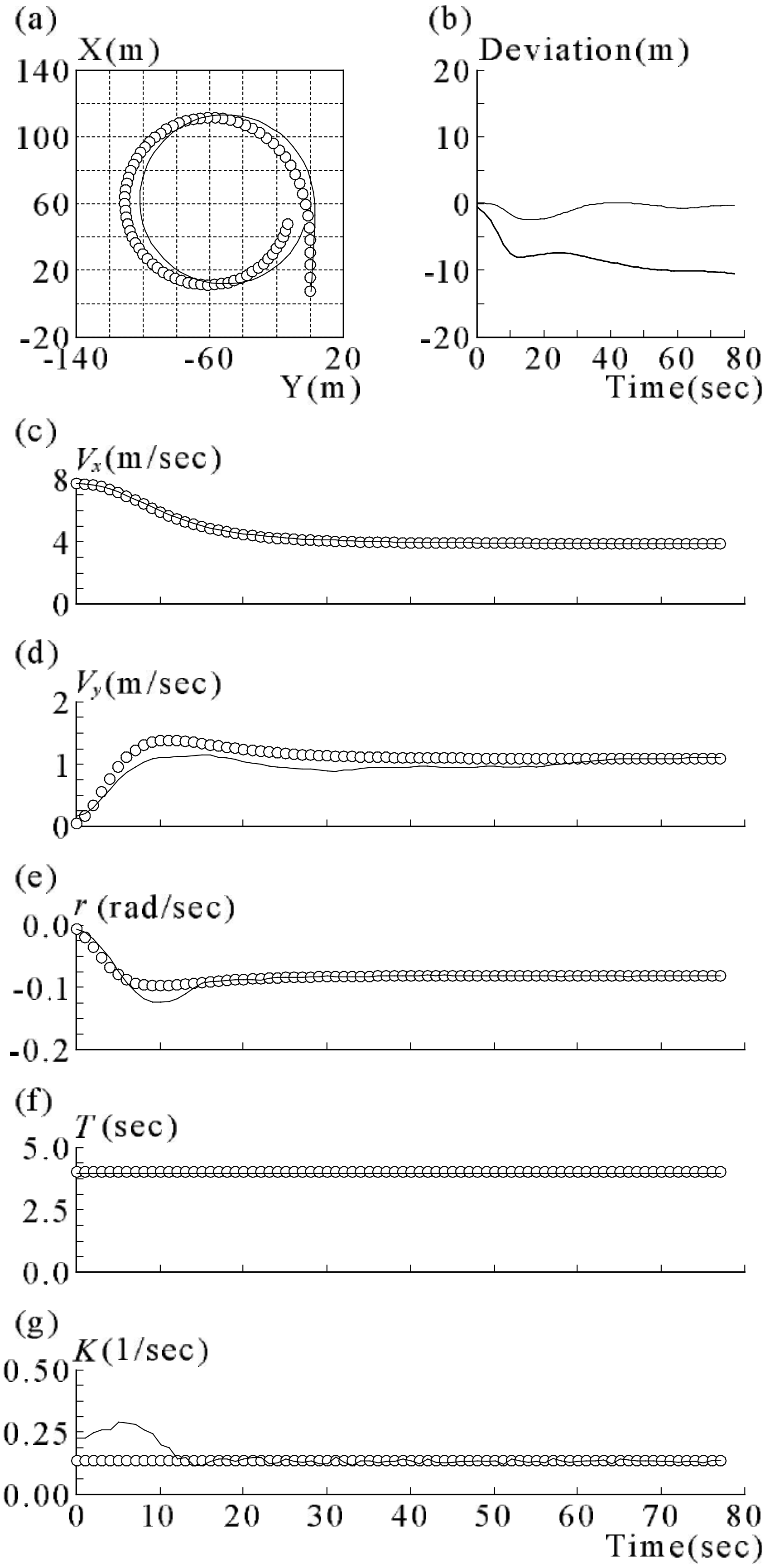

Fig. 6 Comparison of true values and estimated values under port side turning test

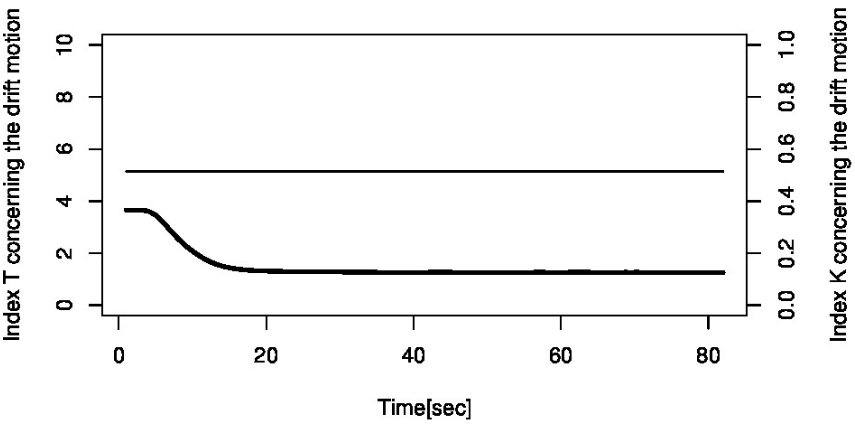

Fig. 7 Estimated maneuverability indices concerning the drift motion under starboard side turning test

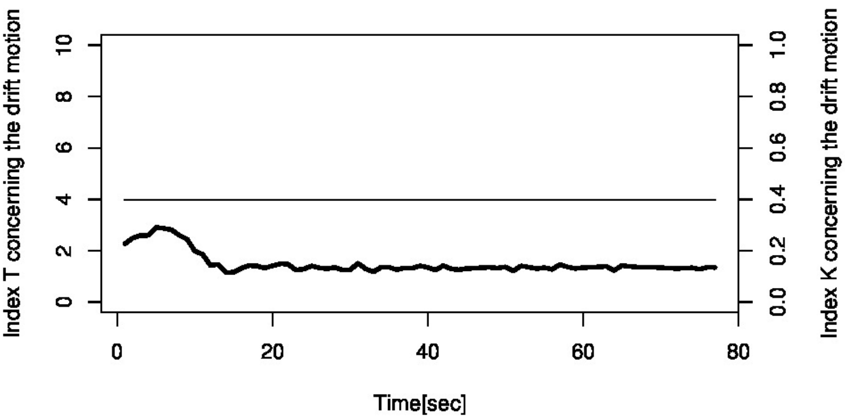

Fig. 8 Estimated maneuverability indices concerning the drift motion under port side turning test

1. The results of the state estimation concerning the maneuvering motion are in good agreement with the true one.
2. It is especially notable that even the ship speed of Y axis, which does not measure directly, can estimate well.
3. As well as the results of the state estimation, the identified maneuverability indices concerning the yaw are in good agreement with the true one which is evaluated by the traditional graphical method.
4. The identified maneuverability indices concerning the drift motion are reasonable as well as the results concerning the yaw, although the true values are unknown.
5. For ship officers, the proposed method is the powerful tool to understand the feature of the maneuvering motion of the ship.

Note that we need to verify the proposed method more in detail based on onboard experiments as well as model experiments. We consider that this is our future task.

ACKNOWLEDGEMENT

This work was supported by JSPS KAKENHI Grant-in Aid for Exploratory Research (Grant Number 26560196).

REFERENCES

Hane, F. (2014) A Comprehensive Identification Method for Vessel Motion Parameters (in Japanese), *Journal of the Japan Society of Naval Architects and Ocean Engineers* 20: 27–38.

Iseki T. and Ohtsu K. (1998) On-line Identification of Ship Maneuverability Indices by Using IIR filter, *Journal of the Society of Naval Architects of Japan* 184: 167–173.

Kitagawa, G. (1998) A Self-organizing state space model, *Journal of the American Statistical Association* 93(443): 1203–1215.

Kitagawa, G. (1996) Monte Carlo Filter and Smoother for non-Gaussian nonlinear state space model, *Journal of Computational and Graphical Statistics* 5(1): 1–25.

Nakamura, K., Ueno, G. and Higuchi, T. (2005) Data assimilation-Concept and Algorithm, *Proc. of the Institute of Statistical Mathematics* 53(2): 211-229 (in Japanese).

Nomoto, K., Taguchi, K, Honda, K. and Hirano S. (1956): On the Steering Qualities of Ships, *Journal of Zosen Kyokai* 101: 75–82 (in Japanese).

Society of Naval Architects of Japan (1981) *Proc. of the 3rd Symposium on ship maneuverability* (in Japanese).

Terada and Kitagawa, G. (2009) Estimation of the Maneuverability under External Disturbance, *Proc. of the 13th International Association of Institutes of Navigation (IAIN2009) World Congress*: 27-30.

Yasukawa, H. and Yoshimura, Y. (2014) Introduction of MMG standard method for ship maneuvering predictions, *Journal of Marine Science and Technology*, DOI 10.1007/s00773-014-0293-y: 1–16.