On Safe Navigation Support System using GPS Compass

Daisuke Terada, *National Defense Academy,* dterada@nda.ac.jp
Masahiro Tamashima, *FLUID TECHNO Co., Ltd.,* mtamashima@fluidtechno.com
Ikuo Nakao, *FLUID TECHNO Co., Ltd.,* inakao@fluidtechno.com
Akihiko Matsuda, *Japan Fisheries Research and Education Agency,* amatsuda@affrc.go.jp

ABSTRACT

For making the onboard use of operational guidance in the IMO second generation intact stability criteria feasible, it is proposed to use a GPS compass for estimating a directional wave spectrum onboard based on Wave Buoy Analogy. As a discussing in 1980s, if the directional wave spectrum can be estimated onboard, then ship motions, a bending stress and so on can be estimated and predicted without direct measurement of them based on the linear superposition theory. Since as the basic theory a Bayesian statistics, namely a general state space modeling procedure, is used, the proposed method can even use under navigation in the following seas. In order to verify the effectiveness of the proposed method, model experiments and onboard experiments are carried out. As the results, it is confirmed the effectiveness of the proposed method, although several future tasks exists.

Keywords: *General state space modelling procedure, Ensemble Kalman Filter, Nonlinear observation.*

1. INTRODUCTION

It goes without saying that it is most important task for a captain, officers and sailors to remain a safe navigation in rough seas. In order to realize this, firstly, under navigation they need to appropriately make the use of operational guidance in the IMO second generation intact stability criteria feasible. In this study, a novel navigation support system using a GPS compass is introduced to realize this purpose. A GPS compass, which was developed in recent years, is new nautical instruments to understand a ship course, position, speed and so on. Especially, the one with built-in a clinometer using acceleration sensor can also measure the ship motions such as pitch motion, roll motion and heave motion, simultaneously. In this paper GPS compass with this function is called the "GPS+M". We focused on this function. That is, by using this GPS compass, we can obtain various information to remain a safe navigation in rough seas.

As well known, in the research field of seakeeping quality, ship motions can evaluate statistically by multiplying response amplitude operators (RAO) based on the linear potential theory and given directional wave spectra. Therefore, if we can prepare the RAO of the ship and can give the encounter directional wave spectrum, then we can evaluate statistical values of ship motions theoretically. In 1980s, this idea had been concretely realized by many ship builders. However, in these systems, officers and sailors had to input several information which are the ship speed, statistical values of encounter waves and so on. Moreover, a transverse metacentric height, namely GM, was also required to calculate the RAO of motions. Consequently, they were not popular. In order to solve one of disadvantages, in 1990s, as well as wave buoy system, an encounter directional wave spectrum under navigation can be evaluated by using the knowledge of statistical science that is especially Bayesian statistics as shown Iseki and Ohtsu [1994] firstly. In recent years, this procedure is called a 'Wave Buoy Analogy (WBA)'. In WBA, the directional wave spectrum can be evaluated by using a RAO concerning ship motions calculated theoretically and a cross spectrum obtained by calculating from measured time series of ship motions. Moreover, Iseki and Terada [2002] showed that ship motions and a longitudinal bending moment can be predicted by using the estimated directional wave spectrum. In this case, the measurement of ship motions can be done by an Inertial Measurement Unit (IMU). Therefore, even if we used the WBA, the ship speed had to input by officers and sailors. It should be noted that the IMU is not an equipment designated by law, although there are the IMU which can take in a signal of GPS.

On the other hand, as mentioned before, the GPS+M can simultaneously measure both of the ship speed and motions. Therefore, disadvantages of the systems developed in 1980s can be solved by using the GPS+M. Moreover, in our recent research [Terada et al. (2016)], we had developed the estimation method of GM based on nonlinear state space modeling procedure which is a type of time series modeling procedure. It means that the estimation of the directional wave spectrum can be automatically achieved by the use of the GPS+M.

From this background, we considered that it can be developed the navigation support system in rough seas which has the function of the statistical prediction. The system contains the estimation of GM, the selection of RAO corresponding the ship speed and the displacement, the calculation of cross spectrum, the estimation of directional wave spectrum and the prediction of ship motions. In these items, especially, as to the estimation procedure of directional wave spectrum, a novel procedure using a general state space modeling is proposed. The feature of this is that at the same time the cross spectrum was calculated, the directional wave spectrum can be evaluated based on filtering process in state estimation of general state space modeling procedure. In this paper, we explain this in detail. The proposed system was verified based on model experiments and onboard experiments. The sample ship is a container ship of coastwise navigation.

2. OUTLINE OF PROPOSED SYSTEM

Figure 1 shows the basic concept of the proposed system. As mentioned above, the most important key technology is the GPS+M. As shown this figure, the information for the ship position, the speed and motions, namely the pitch, the roll and the heave, are simultaneously obtained by it. That is, by using the GPS+M, the time synchronization of each data can be realized naturally. In this system, as to the roll motion, the damping coefficient and the natural frequency are firstly estimated, after that the GM are estimated based on Terada et al. [2016]. As to the detail of this process, see the reference. In this case, if the GM can be estimated, then the RAO for motions with the ship speed and the GM as parameters can be calculated or selected from the database, because the ship speed are given by the GPS+M. Moreover, the cross spectrum of motions can be done automatically by the vector autoregressive modeling procedure [Kitagawa, 2010] based on the minimum AIC (Akaike Information Criterion) [Akaike, 1974] estimation. Thus, the problem of the past research work is solved completely in meaning of the applying of WBA. As to the methodology of WBA, a general state space modeling based on an ensemble Kalman filter (EnKF) [Evensen, 2003] is proposed in after section. Therefore, if an accurate directional wave spectrum can be estimated, then the ship responses such as motions, moment and so on can be estimated without a direct measurement, and the prediction of them can be realized under an assumption of stationarity with respect to waves as well as the past research work.

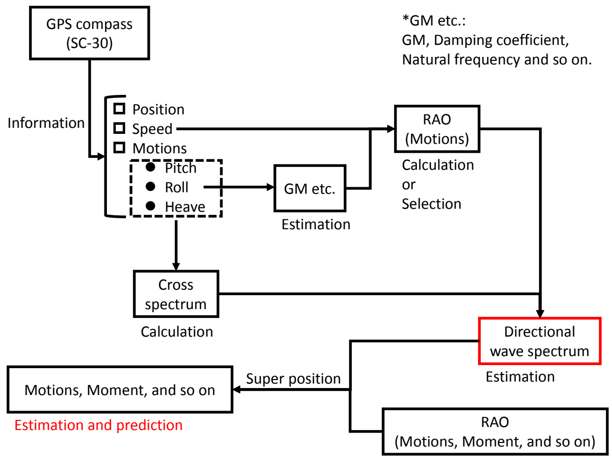


Figure 1: Basic concept of the proposed system.

3. ESTIMATION OF DIRECTIONAL WAVE SPECTRUM

3.1 Modeling

As mentioned before, if ship motions are considered to be linear responses to incident waves, then the cross spectrum of ship motions and the directional wave spectrum are related by the RAO as follows:

$$\Phi_{mn} = \int_{-\pi}^{\pi} H_m(f_e,\chi) H_n^*(f_e,\chi) E(f_e,\chi) d\chi \qquad (1)$$

where f_e is an encounter frequency, $E(f_e, \chi)$ is the directional wave spectrum based on the encounter frequency, Φ_{mn} is the cross spectrum between the m-th and n-th components, $H_m(f_e, \chi)$ is the RAO of the m-th component of the time series, and the notation " *" means the complex conjugate.

On the other hand, the directional wave spectrum expressed by absolute wave frequencies are convenience because of a statistical prediction of ship motions, bending stress and so on. However, in this equation, when the ship runs under the following seas, the relationship between the encounter wave frequency f_e and the absolute frequency f_0 becomes triple valued function problem as shown in Figure 2. According to Iseki and Ohtsu [1994], it can be dealt with this problem appropriately.

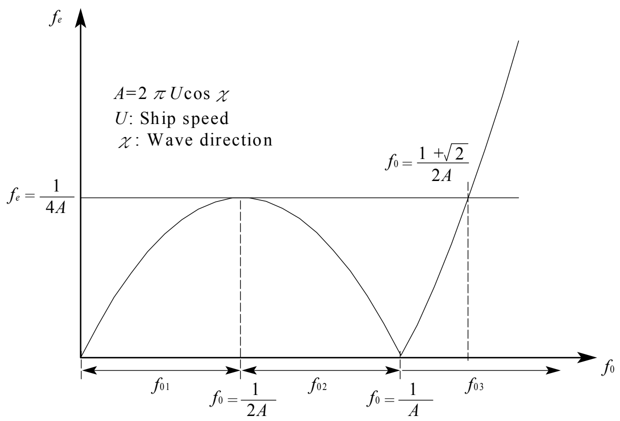


Figure 2: Relationship between encounter wave frequencies and absolute wave frequencies.

Considering this problem in the following seas, the discrete form of the equation (1) can be expressed by the following matrix expression:

$$\begin{aligned}\mathbf{\Phi}(f_e) &= \mathbf{H}(f_{01})\mathbf{E}(f_{01})\mathbf{H}(f_{01})^{*\mathrm{T}} \\ &+ \mathbf{H}(f_{02})\mathbf{E}(f_{02})\mathbf{H}(f_{02})^{*\mathrm{T}} \\ &+ \mathbf{H}(f_{03})\mathbf{E}(f_{03})\mathbf{H}(f_{03})^{*\mathrm{T}}\end{aligned} \quad (2)$$

where f_{01}, f_{02} and f_{03} are the absolute wave frequencies that correspond to the encounter wave frequencies f_e, $\mathbf{\Phi}(f_e)$ is the measured cross spectrum matrix, $\mathbf{H}(f_{0i})$ and $\mathbf{E}(f_{0i})$ (i=1,2,3) denote the matrices of the RAO of ship motions and the directional wave spectrum at the f_{01}, f_{02} and f_{03}, respectively. It should be noted that the number of elements with i = 1 is K, and the number of elements with i = 2 and 3 representing the contribution from the following seas is $K1(<K/2)$. In this equation, since $\mathbf{\Phi}(f_e)$ is a Hermitian matrix, this equation can be reduced to a multivariate regressive model expression using only the upper triangular matrix:

$$\mathbf{y} = \mathbf{A}F(\mathbf{x}) + \mathbf{w} \quad (3)$$

where, $\mathbf{y}$ is the $(9\times l)$ cross spectrum vector which is composed of real and imaginary parts of each element of $\mathbf{\Phi}(f_e)$. Noted that l is the divided number of the spectrum. And $\mathbf{A}$ is the $(9 \times l,\ k \times m)$ coefficient matrix which is composed of products of the RAO of ship motions. Note that k and m are the divided number of the encounter angle and the absolute wave frequency. Moreover, $\mathbf{w}\sim N(0, \mathbf{\Sigma})$ is a $(9 \times l)$ Gaussian white noise sequence vector introduced for stochastic treatment and $F(\mathbf{x})$ is the $(k \times m)$ unknown coefficient vector which is composed of the discretized directional wave spectrum. In the actual calculation, the unknown parameter vector should be expressed in the following form to avoid the estimation of a negative directional wave spectrum:

$$\begin{aligned}&F(\mathbf{x})^{\mathrm{T}} = [\exp(x_1),\cdots,\exp(x_J)] \\ &(\exp(x_j) = E_j(f_0),\ j = 1,\cdots,k\times m)\end{aligned} \quad (4)$$

where, $E_j(f_0) = E(f_0, \chi_k)$, and χ_k denotes a discretized encounter angle.

In this case, if the cross spectrum can be obtained any time step recursively, then the idea of WBA can be extended into the estimation of changing directional wave spectrum with time. That is, equation (3) can be expressed by the following equation:

$$\mathbf{y}_t = \mathbf{A}_t F(\mathbf{x}_t) + \mathbf{w}_t \quad (5)$$

where, in this equation the subscript t means any time step.

In this case, consider that equation (4) is a nonlinear observation model in a general state space model. Moreover, consider a smoothness prior with respect to the change of the directional wave spectrum as a system model of the general state space model. Then, the time varying directional wave spectrum can be dealt with as the problem of the following general state space modelling:

$$\begin{cases} \mathbf{x}_t = \mathbf{x}_{t-1} + \mathbf{v}_t \\ \mathbf{y}_t = \mathbf{A}_t F(\mathbf{x}_t) + \mathbf{w}_t \end{cases} \tag{6}$$

here,

$$\mathbf{x}_t^{\mathrm{T}} = [\ln(x_{1,t}), \cdots, \ln(x_{J,t})]$$
$$F(\mathbf{x}_t)^{\mathrm{T}} = \exp[\ln(x_{1,t}), \cdots, \ln(x_{J,t})].$$

and, $\mathbf{x}_t$ is a state vector, $\mathbf{v}_t$ is a system noise vector, $\mathbf{y}_t$ is an observation vector, $\mathbf{A}_t$ is a state transition matrix and $\mathbf{w}_t$ is an observation noise vector, respectively.

As shown in equation (6), since the observation model is nonlinear, it should be noted that an appropriate state estimation method must be used. As to a nonlinear filtering theory of the state estimation, there are the particle Monte Carlo filter [Kitagawa, 1993], the ensemble Kalman filter (EnKF) [Evensen, 2003] and so on. In this study, the EnKF is used from the viewpoint of the computational time. However, since the EnKF is a type of the Kalman filter, equation (6) including nonlinear observation model cannot be directly used. In order to solve this problem, consider the extended state vector $\mathbf{z}_t$, the extended state transition matrix and the extended observation vector as follows:

$$\mathbf{z}_t = \begin{pmatrix} \mathbf{x}_t \\ \mathbf{A}_t F(\mathbf{x}_t) \end{pmatrix} \tag{7}$$

$$\widetilde{\mathbf{A}}_t = \begin{pmatrix} \mathbf{0}_{(9\times l, m\times k)} & \mathbf{I}_{(9\times l, 9\times l)} \end{pmatrix} \tag{8}$$

$$f_t(\mathbf{z}_{t-1}, \mathbf{v}_t) = \begin{pmatrix} \mathbf{x}_{t-1} + \mathbf{v}_t \\ \mathbf{A}_t F(\mathbf{x}_{t-1} + \mathbf{v}_t) \end{pmatrix} \tag{9}$$

As the result, the equation (6) can be transformed into as follows:

$$\begin{cases} \mathbf{z}_t = f_t(\mathbf{z}_{t-1}, \mathbf{v}_t) \\ \mathbf{y}_t = \widetilde{\mathbf{A}}_t \mathbf{z}_t + \mathbf{w}_t \end{cases}, \tag{10}$$

and since this equation is formally a linear state space representation, the EnKF can be used.

3.2 State estimation

In the EnKF, a state estimation can be done by using ensembles from the probability distribution as well as a particle Monte Carlo filter. Under given the general state space model, the EnKF concretely calculates a predictive distribution $p(\mathbf{z}_t|\mathbf{y}_{t-1})$ and a filter distribution $p(\mathbf{z}_t|\mathbf{y}_t)$ recursively using the M ensemble member $\{z_{t|t}^{(i)}\}_{i=1}^{M}$. According to Evensen [2003], concrete algorithm can be written as follows:

[Step 1] Generate an initial ensemble $\{z_{0|0}^{(i)}\}_{i=1}^{M}$.

[Step 2] Repeat the following steps for n=1~N.

(1) One-step-ahead prediction

(a) Generate an ensemble $\{v_t^{(i)}\}_{i=1}^{M}$ of the system noise.

(b) For i=1,…, M, compute the following equation:

$$z_{t|t-1}^{(i)} = f_t(z_{t-1|t-1}^{(i)}, v_t^{(i)}) \tag{11}$$

(2) Filter

(a) Generate an ensemble $\{W_t^{(i)}\}_{i=1}^{M}$ of the observation noise.

(b) For i=1,…, M, compute the following equations:

$$\breve{z}_{t|t-1}^{(i)} = z_{t|t-1}^{(i)} - \frac{1}{M}\sum_{j=1}^{M} z_{t|t-1}^{(j)} \tag{12}$$

$$\hat{V}_{t|t-1} = \frac{1}{M}\sum_{j=1}^{M} \breve{z}_{t|t-1}^{(j)} \breve{z}_{t|t-1}^{(j)\,T} \tag{13}$$

$$\breve{W}_t^{(i)} = W_t^{(i)} - \frac{1}{M}\sum_{j=1}^{M} W_t^{(j)} \tag{14}$$

$$\hat{\Sigma}_t = \frac{1}{M-1}\sum_{j=1}^{M} \breve{W}_t^{(j)} \breve{W}_t^{(j)T} \tag{15}$$

$$\hat{K}_t = \hat{V}_{t|t-1} \widetilde{\mathbf{A}}_t^{T} \left(\widetilde{\mathbf{A}}_t \hat{V}_{t|t-1} \widetilde{\mathbf{A}}_t^{T} + \hat{\Sigma}_t \right)^{-1} \tag{16}$$

(c) For i=1,…, M, compute the following equation:

$$z_{t|t}^{(i)} = z_{t|t-1}^{(i)} + \hat{K}_t \left(\mathbf{y}_t + \breve{W}_t^{(i)} - \widetilde{\mathbf{A}}_t z_{t|t-1}^{(i)} \right) \tag{17}$$

4. RESULTS AND DISCUSSIONS

4.1 Model experiments

In order to verify the proposed procedure, we firstly carried out the free running model experiments concerning a container ship at the marine dynamics basin belonging to Japan Fisheries Research and Education Agency. The principal perpendiculars and the photo are shown in Table 1 and Figure 1, respectively.

Table 1: Principal particulars of the sample ship.

L_{pp}	85.0 m	GM	0.828 m
B	14.0 m	T_ϕ	13.3 sec
d_m	3.54 m	k'_{yy}	0.264
W	2993.21ton		

Note: Scale ratio = 1/33

Figure 2: Photo of the sample ship.

One of the results of the model experiments is shown in this subsection. The conditions in the model experiments are as follows:

- ☐ The model ship speed is corresponding to 10[knots] in actual ship.
- ☐ The encounter angle relationship between the ship course and the wave direction is 0[degrees], that is, the model ship ran under the following seas.
- ☐ The measurement device is the Fiber Optic Gyro (FOG) sensor made by Tamagawa seiki Co., Ltd., and its sampling rate is 20[Hz]. It should be noted that a vertical acceleration was used for the analysis, since in model experiments the heave can not be measured.
- ☐ The waves are the long-crested irregular waves, are reproduced by the conditions in which the significant wave height $H_{1/3}$ is 1[m] and the mean period T_{01} is 6[sec].
- ☐ Note that the results of the model scale have been transformed in to the value of the actual ship.

As preparation of the estimation of the directional wave spectrum, as shown in Figure 3 the 100 data set from one record of the measured time series data such that the number of analysis data always becomes 300 samples were made, because the measurement time in the model experiment has the constraint. It should be noted that to use 300 samples is decided by the viewpoint of the calculation time.

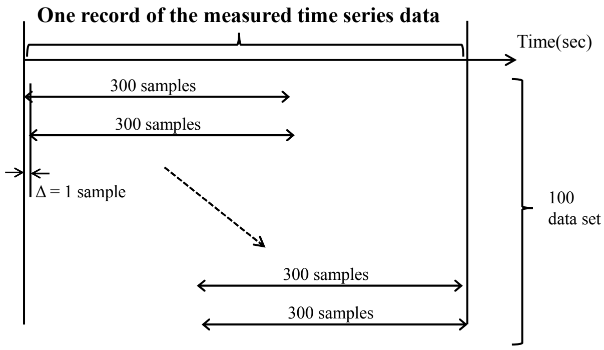


Figure 3: Schematic diagram concerning the contraction of the data set.

From Figure 4 to Figure 6 show the three kinds of characteristics, namely significant wave height, wave mean period and wave direction, obtained by the integral of the estimated directional wave spectrum, respectively. In these figures, the horizontal axis indicates the sample data number, and the vertical axis indicates the characteristics of the estimated directional wave spectrum. Figure 4 shows the significant wave height, Figure 5 shows the mean period, and Figure 6 shows the direction of the wave, respectively. From these figures, it can be confirmed that each characteristic of the estimated directional wave spectrum converges to the set values with time, even though the condition of the encounter angle with respect to waves is the following seas. Therefore, it can be considered that the proposed method for the estimation of the directional wave spectrum is effective.

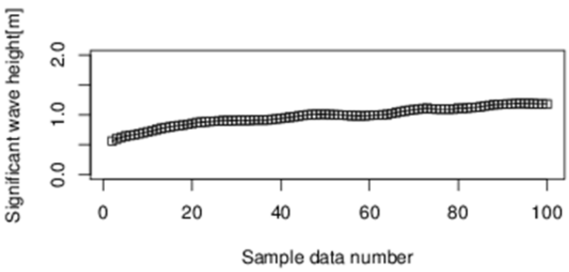


Figure 4: Estimated significant wave height.

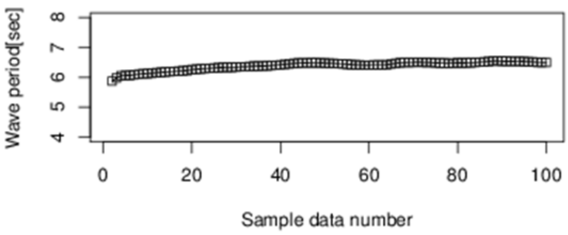


Figure 5: Estimated mean period.

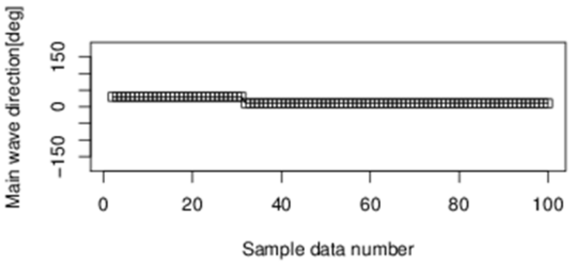


Figure 6: Estimated main wave direction.

4.2 Onboard experiments

One of the results of the onboard experiments is shown in this subsection. The sample ship is the same one used in the model experiments. In the onboard experiments, as the GPS compass, the "SC-30" made by FURUNO ELECTRIC CO., LTD. was used. The SC-30 was set as the Figure 7 at the upper of flying bridge of the sample ship. The data which was measured at 14 [UTC] o'clock on Feb. 8, 2014 is used in the analysis. In this case, the sampling time is the 1.0 [sec]. Figure 8 shows the ship's position where data was measured.

Figures 9 (a) ~ (e) show the time series between 1,200 [sec] was measured by the SC-30. From top to bottom, the ship course, the speed, the pitch, the roll and the heave are shown, respectively. From these figures, it can be seen that the sample ship bounds for the east at the ship speed about 11 [knots]. And, it can be also seen that the motions are large. Here, these data were analyzed every 300 samples (300 [sec]). It is called that the first 300 samples is 'case01', the second 300 samples is 'case02', the third 300 samples is 'case03' and the last one is 'case04', respectively.

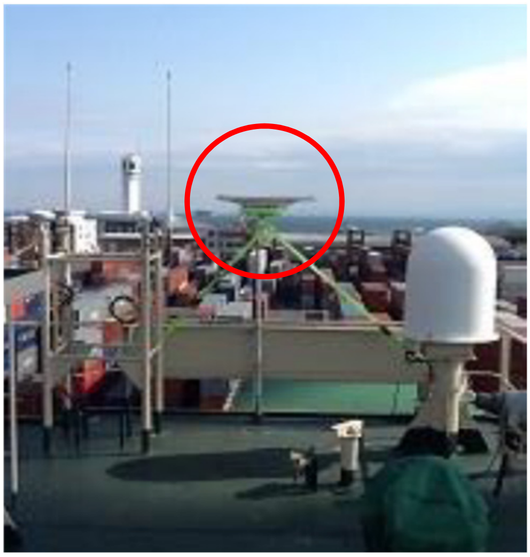
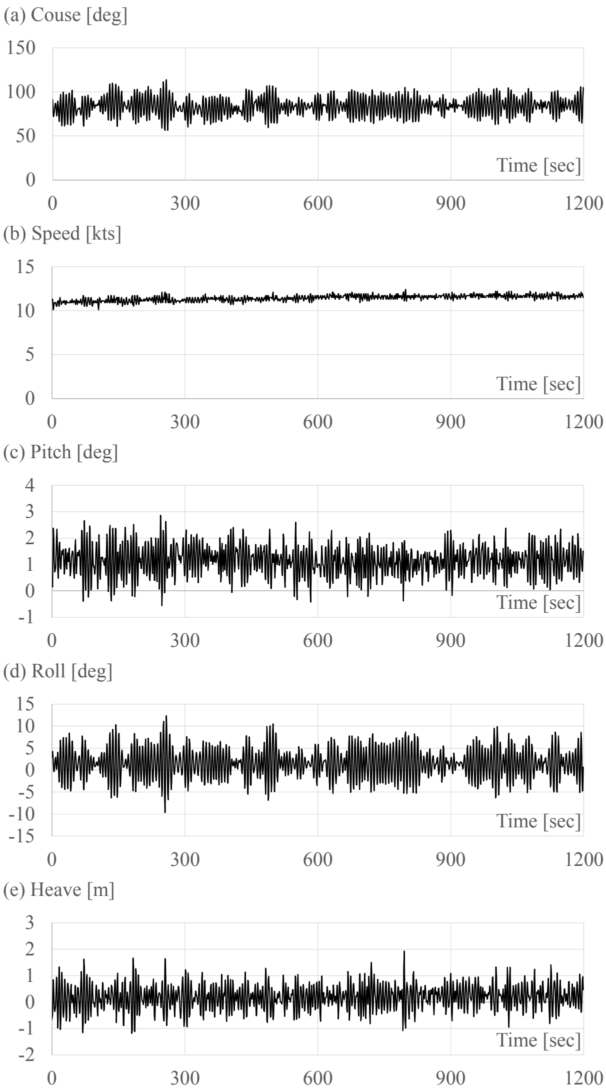


Figure 7: Photo of installation state of the SC-30.

Figure 8: Ship's position where data for the analysis was measured.

Table 2 shows the results of the analysis and the results of the wave prediction in Japan Meteorological Agency (JMA) [JMA(A), 2017]. From this table, as to the significant wave height, it can be seen that the estimated values by the proposed method are good agreement with the wave prediction values in the JMA, though the target time is slight different. However, as to the wave mean period, both results are slight different, moreover as to the wave direction, both results are quite different. As one of this cause, it is considered that the wave prediction method in the JMA can not take multi-directionality into consideration as shown Sasa et al. [2015], although our proposed method can deal with multi-directionality of waves. As the reference information, we investigated the wind information of the JMA observation point, which is Munakata city, Fukuoka Prefecture, closest to the ship's position [JMA(B), 2017]. According to this records, the direction varied from SSE to WSW, and the velocity varied from 1.5 [m/s] to 1.0[m/s], respectively. Therefore, at least, as to the wave direction, it can be considered that the accuracy of the wave prediction values in the JMA is low, because there is the fact in which the direction of the wind and wind waves is almost same. Note that as to this, it is necessary to verify more in detail.



Figures 9: Time series for the data analysis.

Table 2: Comparison with the estimated values by the proposed method and the wave prediction values in the JMA.

	$H_{1/3}$ [m]	T_{01} [sec]	Wave direction Main	2nd
case01	2.37	6.28	South	North
case02	2.37	6.28	South	NNW
case03	2.35	6.27	South	North
case04	2.33	6.25	South	NNW
JMA [UTC1200]	2.0	9.0	NNE	
[UTC2400]	1.6	4.0	NNW	

5. CONCLUSIONS

In this research, from the view point in which under navigation ship's crews appropriately make the use of operational guidance in the IMO second generation intact stability criteria feasible, the safe navigation support system using GPS compass is introduced. The system contains the estimation of GM, the selection of the response amplitude operator corresponding the ship speed and the displacement, the calculation of cross spectrum, the estimation of directional wave spectrum and the prediction of ship motions. In these items, especially, as to the estimation procedure of directional wave spectrum, a novel procedure using a general state space modeling was proposed. The feature of this is that at the same time the cross spectrum was calculated, the directional wave spectrum can be evaluated based on filtering process in state estimation of general state space modeling procedure. In order to verify the effectiveness of the proposed method for the estimation of directional wave spectrum, the model experiments and the onboard experiments are carried out. Obtained findings are summarized as follows:

(1) From the results of the model experiments, under the condition in which the ship motions exist, it can be confirmed that the estimated directional wave spectrum based on the proposed method is good agreement with the set one, since the characteristics obtained by the integral of the estimated directional wave spectrum converge the set values with time.

(2) From the onboard experiments, as to the significant wave height, it can be seen that the estimated values by the proposed method are good agreement with the wave prediction values in the Japan Meteorological Agency, though the target time is slight different. However, as to the wave mean period, both

results are slight different, moreover as to the wave direction, both results are quite different. Therefore, as a future task, it is necessary to verify this reason more in detail comparison with an onboard experiment using a wave buoy and a wave RADAR.

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