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Onboard Wave Sensing with Velocity Information GPS

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ABSTRACT: Even though it is essential that the wave information promotes greater safety also efficiency to navigate and/or operate a ship not only ocean going but also docking/landing, it is very difficult to sense a wave information such as wave heights and periods or wave lengths in real time at the present time. On the other hand, the Velocity Information (VI) GPS is developed as the stand-alone 3D velocities measurement equipment of which accuracies are precise (less than 1 cm/s) and the coverage is all over the world. It is able to drive the wave information from the time history of not only wave amplitudes but also wave velocities. The algorithm to sense the wave information such as not only significant wave height but also plural wave heights and period intervals of encounter was presented by the authors in IAIN2009 and ANC2010. In this paper, the introduction and the performance of wave sensing with VI-GPS and some results of onboard experiments are described and discussed.

1 INTRODUCTION

SDME (Speed and Distance Measurement Equipment) which presents two axes velocities OG (Over the Ground) to ship master and/or pilot, such as Doppler SONAR, etc. is manufactured as the best application of safety docking to dolphin or berth for VLCC, etc.

Recently it is also developing to assist maneuvering in approach to a dolphin/berth using high accuracy DGPS or RTK-GPS which requires communication to base-station, and now the new technology on GPS, called VI-GPS (Velocity Information GPS) and presents very high accuracy velocities stand-alone or without communication to base-station, is coming to onboard application (Tatsumi, et al., 2009), (Yoo, et al., 2009), and Okuda, et al. (2008) presented the trade-off between accuracy and response in application of docking velocity that means the performance of Velocity Information is affected not only by the accuracy but also by the relationship between the time lag of SDME and her math or time constant of maneuverability.

Meanwhile, recently it is often taken to dock not only to a dolphin/berth but also to a navigating vessel called STS (Ship To Ship) operation (Yoo, et al., 2009). In case of STS operation, it is taken on open-sea or deep-sea, so the external forces such as current, wave and wind affect ship maneuvering, and onboard sensing external forces are essential to make a good solution not only for safety but also for efficiency. So, it is the trade-off between safety and economical issues. Although it is very important issues to efficiently apply the SDME, but onboard sensing current and/or wave effect is very difficult because of the low responsibility and/or poor performance of STW (Speed Through the Water) (Arai, et al. 1983). So, Arai, et al. (2009), (2010) developed the algorithm to sense the current and wave effect without two axes SDME TW (Through the Water).

In this paper, at first VI-GPS, at second the developed algorithm to sense external forces such as wave and current are introduced, at third the onboard experiments, results and evaluations are presented and discussed, finally it is concluded that proposed algorithm and availability of onboard wave sensing with VI-GPS will be essential to ship operation not only docking or STS operation but also ocean going, etc.

2 VELOCITY INFORMATION GPS

2.1 *Outline of VI-GPS*

VI-GPS consists of front-end GPS receiver to measure carrier phases at every epoch and processing unit which has the differential system of carrier phases and phased and/or coded GPS positioning system.

VI-GPS positioning system is same as conventional system, so it is able to position fix within the accuracy of several meters. In the conventional GPS the measurement of carrier frequency with Doppler shift drives the velocities or SOG (Speed Over the Ground) and COG (Course Over the Ground), but VI-GPS measures carrier phase at every epoch Φ_i (m) and calculates the time difference of carrier phases between serial epochs $\delta\Phi_i$ is following (Tatsumi, et al. 2008):

$$\delta\Phi_i = \Phi_i - \Phi_{i-1} = \delta\rho + c \cdot (\delta dt - \delta dT) + \epsilon_{\delta\Phi} \quad (1)$$

where, ρ is the geometric distance between a satellite and a receiver (m); c is the light speed in vacuum (m/s); dt and dT are the receiver and satellite clock error (s); $\epsilon_{\delta\Phi}$ is the measurement noise and errors which are not able to be modelled; and the symbol δ is the time difference operator.

Time differential observation drives cancelling propagation errors and little clock errors in the receiver and satellite, so VI-GPS is a stand-alone system which presents high accuracies of velocities without referential stations around the world.

2.2 *Accuracies of Ship's Velocities*

The essential maneuvering information is categorized and shown in Figure 1. In this figure, Heading, ROT (Rate Of Turning) and Wind Speed and Direction are measured by the conventional instruments, and controllable parameters of ship maneuvering are rudder motion (RUD) and/or propeller revolution (RPM), etc. Ship's speed SOG and course OG are measured by two axes SDME OG such as Doppler SONAR, etc.

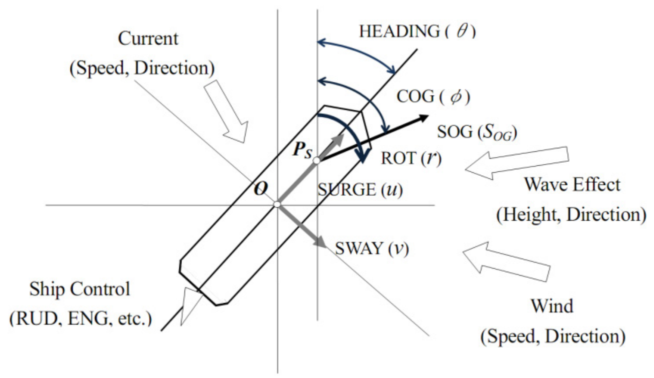

Figure 1. Maneuvering Information

To maneuver for safety and economically especially in docking, longitudinal and lateral velocities at a Setting Point $\boldsymbol{P_S}$, and the disturbances such as wind, current and/or wave information are essential. The relationship between velocities at Setting Point $\boldsymbol{P_S} = (X_S, Y_S)$ and Surge/Sway at the Center of Ship $\boldsymbol{O}$ are following (Arai, et al. 2010):

$$U_{lon} = u - r \cdot Y_S$$
$$U_{lat} = v + r \cdot X_S \quad (2)$$

where, U_{lon} and U_{lat} are longitudinal and lateral velocities at Setting Point of the sensor $\boldsymbol{P_S}$; $\boldsymbol{U} = (u, v)$ u and v are surge and sway (m/s); and r is ROT (rad/s).

In case of using VI-GPS, it is able to measure SOG/COG, so the relationship between SOG/COG at Sensor Position $\boldsymbol{P_{GPS}} = (X_{GPS}, Y_{GPS})$ is following:

$$u_{OG} = S_{OG} \cdot \cos(\emptyset - \theta) + r \cdot Y_{GPS}$$
$$v_{OG} = S_{OG} \cdot \sin(\emptyset - \theta) - r \cdot X_{GPS} \quad (3)$$

where, $\boldsymbol{U_{OG}} = (u_{OG},\ v_{OG})$ is the vector of two axes velocities OG at center of ship $\boldsymbol{O}$.

Considering the error propagation from sensor error, the deviations of surge and sway $(\mathrm{d}u_{OG}, \mathrm{d}v_{OG})$ are resolved and following with total differential equation:

$$\mathrm{d}u_{OG} = \mathrm{d}u_{GPS} + v \cdot (\mathrm{d}\theta + r \cdot \Delta t) + Y_{GPS}\mathrm{d}r \cdot (1 + \Delta t)$$
$$\mathrm{d}v_{OG} = \mathrm{d}v_{GPS} - u \cdot (\mathrm{d}\theta + r \cdot \Delta t) - X_{GPS}\mathrm{d}r \cdot (1 + \Delta t) \quad (4)$$

where, deviation of longitudinal/lateral velocity by VI-GPS is $(\mathrm{d}u_{GPS} = \mathrm{d}V_{NS}\cos\theta + \mathrm{d}V_{EW}\sin\theta)$ and $(\mathrm{d}v_{GPS} = \mathrm{d}V_{EW}\cos\theta - \mathrm{d}V_{NS}\sin\theta)$; V_{NS} and V_{EW} are the velocities of N-S and E-W direction components by GPS; and Δt is time difference between VI-GPS and Compass.

The variances of surge and sway are driven by Equation 4 and following, if every parameter is independent statistically:

$$\sigma_{u_{OG}}{}^2 = \sigma_{GPS}{}^2 + v^2\sigma_\theta{}^2 + Y_{GPS}{}^2\sigma_r{}^2$$
$$\sigma_{v_{OG}}{}^2 = \sigma_{GPS}{}^2 + u^2\sigma_\theta{}^2 + X_{GPS}{}^2\sigma_r{}^2 \quad (5)$$

where, the variances of VI-GPS, Heading and ROT are $\sigma_{GPS}{}^2$, $\sigma_\theta{}^2$ and $\sigma_r{}^2$.

According to Equation 4 and 5, the countermeasure to decrease the deviations and variances of surge and sway are described as follows:

1 To install GPS antenna at same point as setting point where ship master requires to docking.

2 In case of STS operation longitudinal velocity is not so slow, so it affects the accuracy of lateral velocity with the performance of compass.
3 Synchronizing between sampling time of VI-GPS and heading/ROT information is essential to keep high accuracy in ship's turning.
4 In case of sensing wave effect, to install GPS antenna at the ship's center.

SOG or STW (Speed Through the Water) according to logical consideration such as sensor position and setting point as discussed Equation 2 to 5, but also it is essential to consider fitting error of sensor, effect of wake in STW, etc. (Arai, et al., 1983).

2.3 *Performance of VI-GPS*

Two axes velocities are precisely measured by VI-GPS, but in the stage of converting to surge and sway from COG and SOG (Equation 3) there are some troubles which caused by mismatching of timing between onboard communication systems in Compass and VI-GPS. This problem should be surveyed using correlation function or another method, and the time difference or synchronization should be within minimum effects. So, in case of high ROT such as under turning, the effect of mismatching would increase and it would be difficult to maintain high accuracy.

The performance of VI-GPS is following and numerical performance is shown in Table 1:

1 VI-GPS works stand-alone and presents high accuracy velocities or SOG and COG.
2 VI-GPS has a good response to measure as shown in Table 1, but total system response should be limited because of on-board Navigational Information system's data interval.
3 Accuracy of VI-GPS is excellent, and onboard measuring two axes velocities essential with heading information is available.
4 RAIM (Radio Autonomous Integrity Monitoring) function is much important to gain the reliability of ship maneuvering.

Table 1. Performance of VI-GPS

The accuracy of Velocity	less than 1cm/s
Sampling Time	5 Hz (0.2 s)
Responsiveness	less than 1 s
Stand alone	Yes
Coverage	All over the world

3 ALGOLITHM FOR ONBORD WAVE SENSING

3.1 *Effect of the External Forces*

The external forces which affect ship operation are wind, current and wave. The effect of wind is easily able to be sensed in real time and to be countermeasured for safety navigation, but it is very difficult to sense the effects of current and/or wave in real time. The effects of current and wave $\boldsymbol{U} = (u,\ v)$ are included in the difference between surge/sway OG $\boldsymbol{U_{OG}} = (u_{OG}, v_{OG})$ which are easily measured in high accuracy using two axes SDME OG such as Doppler SONAR and VI-GPS, and surge/sway TW $\boldsymbol{U_{TW}} = (u_{TW}, v_{TW})$ which are not so easy able to be measured.

Current is steady for short term, so the current components (speed and/or direction) will be easily able to be sensed using LPF (Low Pass Filter) or moving average method. After sensing current, the wave effect component will be sensed to subtract from current component.

The advanced algorithm shown as Figure 4 which has been developed to improve the demerit of former algorithm which is able to sense the wave direction not all around but the limit measurement only for 90 deg. and the average wave length. So we developed the advanced algorithm which is able to sense the direction, length and height of plural waves using the Fast Fourier Transform. The disturbance forces except DC or very low frequency components which mean current are following:

$$u = -\sum_i F_{lon}(\omega_i) \cdot A_{lon_i} \cdot \omega_i \cdot \sin(-\omega_i t + \varphi_i)$$

$$v = -\sum_i F_{lat}(\omega_i) \cdot A_{lat_i} \cdot \omega_i \cdot \sin(-\omega_i t + \varphi_i)$$

$$\omega_i = \omega_{O_i} - K_i \cdot S_{OG} \cdot cos(\beta_i - \emptyset) \qquad (6)$$

where, angular frequency of encounter isω_i (rad/s) ; angular frequency of wave is ω_i (rad/s); period of encounter is $T_i = 2\pi/\omega_i$ (s); wave length of encounter $\lambda_i = 2\pi/K_i$ (m); wave direction β_i (deg.); wave amplitude of longitudinal/ lateral components are A_{lon_i}, A_{lat_i} (m); response function of longitudinal/lateral ship motion are $F_{lon/lat}(\omega_i)$ and i means i-th wave components.

Surge/sway are affected by ship's motion, and it is possible to solve the response functions or models of longitudinal and lateral motions of ship using differential equations. It will be assumed that these response models are primary response, so response functions are defined as follows:

$$V_{lon/lat}(\omega_i) = 1/\sqrt{1 + (T_{lon/lat} \cdot \omega_i/2\pi)^2} \qquad (7)$$

where, $T_{lon/lat}$ is time constant of each response model.

The values $\boldsymbol{U} = (u, v)$ are observed during proper time, then the wave components which mean spectrum amplitudes $V_{lon/lat}\ (\omega_i)$ and phases $\psi_{lon}\ (\omega_i)$ are resolved by FFT. So, it is able to drive the wave information from these data and follows:

$$V(\omega_i) = \sqrt{V_{lon}(\omega_i)^2 + V_{lat}(\omega_i)^2}$$
$$B(\omega_i) = \mathrm{Atan2}[\mathrm{sign}_{lon} \cdot V_{lon}(\omega_i), \mathrm{sign}_{lat} V_{lat}(\omega_i)] \quad (8)$$

where, $V(\omega_i)$ and $\mathrm{B}(\omega_i)$ are speed and direction of water particles by wave at each frequency; and $\mathrm{sign}_{lon/lat}$ means sign of $V_{lon/lat}(\omega_i)$ according to $\mathrm{B}(\omega_i)$.

The examples of FFT results are following:

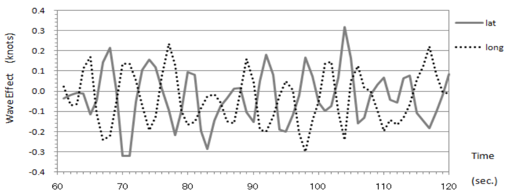

Figure 2. The time series of wave effect or $\boldsymbol{U}$ are sampled at every 1 s during 1 min. Plural waves are found and roughly reading shows that the average period is less than 10 s

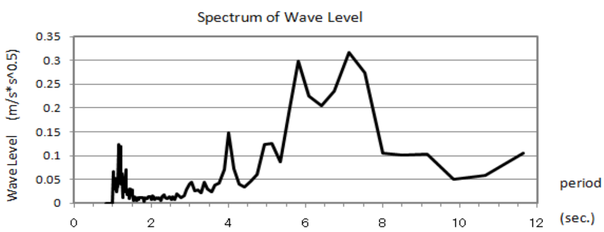

Figure 3. Sample Result of FFT (128 points). The unit of amplitude spectrum is shown as "m/s*s^2", it means amplitude of velocity at every $\sqrt{\mathrm{Hz}}$. The unit of amplitude spectrum should be "(m/s)/$\sqrt{\mathrm{Hz}}$". The result clearly shows that five waves exist and their periods. The longest one is 7.5 s and the shortest one is 1.5 s

3.2 *Algorithm of Onboard Wave Sensing*

The flow chart of proposed algorithm is shown in Figure 4, and consists of 5 parts as follows.

1 MMG: this part calculates to gain the two axes velocities TW $\boldsymbol{U}_{TW}$ which are longitudinal velocity u_w (here we call as Surge TW) and lateral velocity v_w (Sway TW) without effect of current and wave or only calculated from propeller thrust (ENG), rudder motion (RUD) and wind effect (Arai, et al., 1990).

2 CONVERT: Measured COG ϕ and SOG S_{OG} are converted using heading ?? and sensor position to gain the two axes velocities OG $\boldsymbol{U}_{OG}$ which are longitudinal velocity OG u_{OG} (Surge OG) and lateral velocity v_{OG} (Sway OG).

3 SUB: To gain the current including wave effect, the subtraction from $\boldsymbol{U}_{OG}$ to $\boldsymbol{U}_{TW}$ and is executed. $\boldsymbol{U} = \boldsymbol{U}_{OG} - \boldsymbol{U}_{TW}$: $\boldsymbol{U}$ consists of the velocity components of external forces which are affected ship's math, and is named as disturbances. After subtraction, the coordinate system of $\boldsymbol{U}$ is converted from the ship coordinates to the terrestrial ones.

4 SPLITTER: It is done to split from $\boldsymbol{U}$ to current $\boldsymbol{Uc}$ and wave effect $\boldsymbol{Uw}$ using the Low Pass Filter (LPF) and the High Pass Filter (HPF). Output from LPF consists of the current component $\boldsymbol{Uc}$ and cut-off frequency of LPF should be set as lower as possible and usually be set as 1/30 or 1/60 Hz which is lower than wave frequency.

5 FFT: FFT gains the frequency component of wave effect $\boldsymbol{Uw}$. From the results of FFT, the amplitude and direction of wave effect $\boldsymbol{Uw}$ with respect to each frequency or period of wave are possible to be sensed according to Equation 6.

3.3 *Accuracies of Wave Information*

The wave amplitude at each frequency is drawn from the wave velocities Equation 6~8 and shown as Equation 9.

$$A(\omega_i) = \frac{U(\omega_i)}{F(\omega_i)\cdot\omega_i} \quad (9)$$

So, it is able to drive the accuracy of wave amplitude which is following:

$$\mathrm{d}A = \frac{\mathrm{d}U}{F(\omega_i)\cdot\omega_i} - \frac{\mathrm{A}(\omega_i)\cdot\mathrm{d}\omega}{\omega_i} \quad (10)$$

$$\sigma_{A_i} = \frac{1}{\omega_i}\sqrt{\frac{\sigma U^2}{F(\omega_i)} + A(\omega_i)^2 \cdot {\sigma_\omega}^2} \quad (11)$$

$$\sigma_\omega = 2\pi \cdot \frac{f_s}{N} \quad (12)$$

where, σ_A, σ_U and σ_ω are root mean square of variances of wave amplitude, measured velocity and frequency; f_s is sampling frequency (Hz); and N is sampling number of FFT.

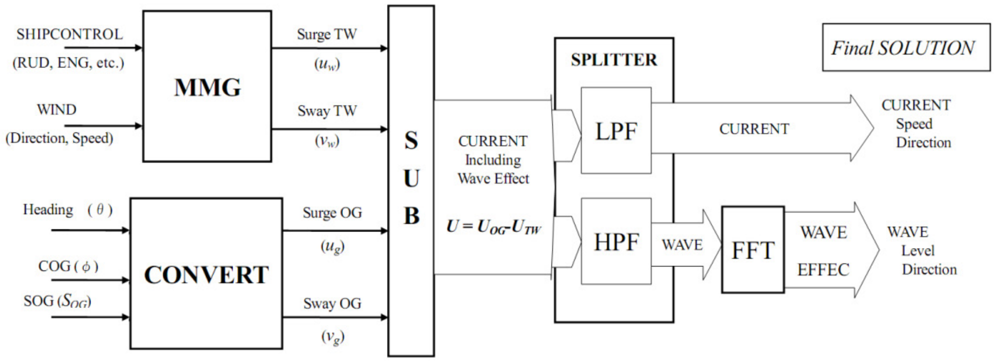

Figure 4. Flow Chart on Algorithm of Onboard Wave Sensing

According to Equation 11, the variance of sensed wave height consists of two parts. The former is affected by the ship's mass or the response of ship's motion, and the latter is proportional one as sampling parameters.

Using FFT, the every span of sequential frequencies is same. In case of short period, the number of wave in the width of periods increases. So, it is expected that the accuracy of wave information will increase according to averaging in the width of periods, and these are following:

$$\sigma_{A_i}{}' = \frac{\sigma_{A_i}}{\sqrt{\mathrm{INT}\left(4(4f^2-1)\cdot\frac{N\Delta t}{\Delta T}\right)}} \qquad (13)$$

where, $\Delta t = 1/f_s$ (s); ΔT is period interval (s); and INT means integer of ( ).

1 In case of onboard experiment, accuracy of wave height is within approximately 10 cm until period is under 15 s and it is available to observe the wave information.
2 Using VI-GPS, it is not necessary to make a data-link to base station such as RTK-GPS.
3 In case of large ship such as VLCC, the accuracy is not so good (1.5 m) because of her ship's response.

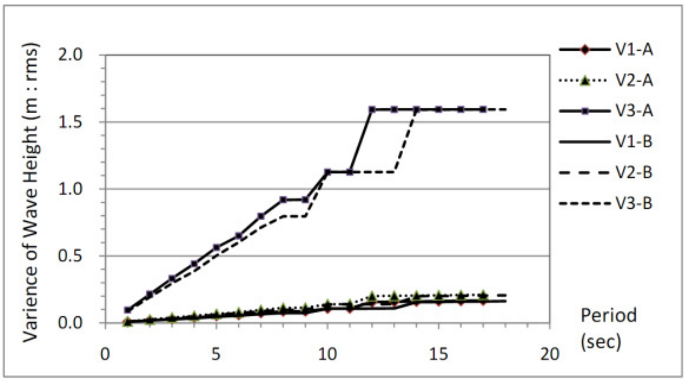

Figure 5. Expected variances of Wave Height. (V1: 150GT T/S, V2:500GT T/S, V3:VLCC) and (A means "f_S = 5 Hz, N=1024", B means "f_S=1 Hz, N=256")

4 EVALUATION

4.1 *Onboard Experiment*

To evaluate the performance of the advanced system, the onboard data are used in the former paper (Yoo, et al., 2009) which used "T/S Shioji-maru" belong to Tokyo University of Marine Science and Technology was executed. Her principals are shown in Table 1, and the installation of VI-GPS antenna used in this experiment is shown in Figure 6.

Table 2. Principals of T/S Shioji-maru.

Gross Tonnage	425 tons
Lpp	46.00 m
Breadth	10.00 m
Depth	6.10 m
Draught	3.00 m
Displacement	785 DWT
Mean wind direction	165 deg
Mean wind speed	5.3 knots
Data length	1200 s
Sampling freq.	1 Hz

Figure 6. Arrangement on the Flying Bridge of T/S Shioji-maru. (VI-GPS ANT is shown in the white circle)

4.2 *Results of Onboard Experiments*

To survey the availability of the application of the system using the maneuvering data or onboard wave sensing, experimentation was executed.

STW Information includes some fluctuation, so it was confirmed that conventional Speed Log is not applicable to do with high precise and higher response. It is easily supposed that according to a poor performance of Speed Log it was affected by the wake and/or propeller effects in case of worth installation.

The advanced system modified to add the FFT according to sensing the wave effect. In this experiment original data sampling time is 1 s, so the performance of wave information should be affected by sampling time. So performance of sensing wave and/or current at experimented and ideal are shown in Table 3.

Table 3. Performance of FFT

Items	Experiment Performance	Ideal Performance
Sampling Frequency	1 Hz	5 Hz
Sampling Duration	256 s	204.8 s
Sampling points	256	1024
Frequency Range	1/256 ~ 0.5 Hz	1/102.4 ~ 2.5 Hz
Period Range	2 ~ 256 s	0.4 ~ 102.4 s

The results of wave effect information are shown in Figure 7. Sampling Points of FFT used as shown in the left column of Table 3 was 256, so the resolution of frequency is higher in short period. Figure 7 were recalculated and reformed the period width is approximately 1 s. In shorter period or higher frequency range will be averaged and gain the accuracy, so the results are shown under the maximum period 17 s.

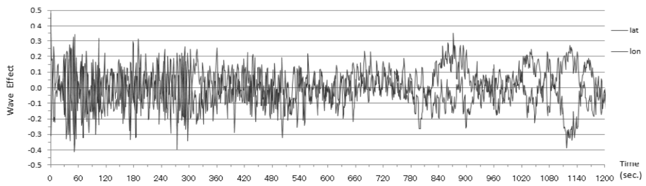

Figure 7. Current and Wave Information on board Experiment

The sea area of the executed experiments was off Tateyama at the East side of Tokyo Bay entrance, the course of T/S Shioji-maru was approximately 040 deg including changing course to 030 deg at 900 s. The observed wave information during the experiments was “light breeze”, but no recorded of the wave direction.

The solutions of wave effect are shown in Figure 8. The left graphs show wave level of which the unit is meter same as wave height, and lower ones show wave direction which is relative motion to ship not true motion. The parameter of the horizontal axis of all of graphs is the period of encounter.

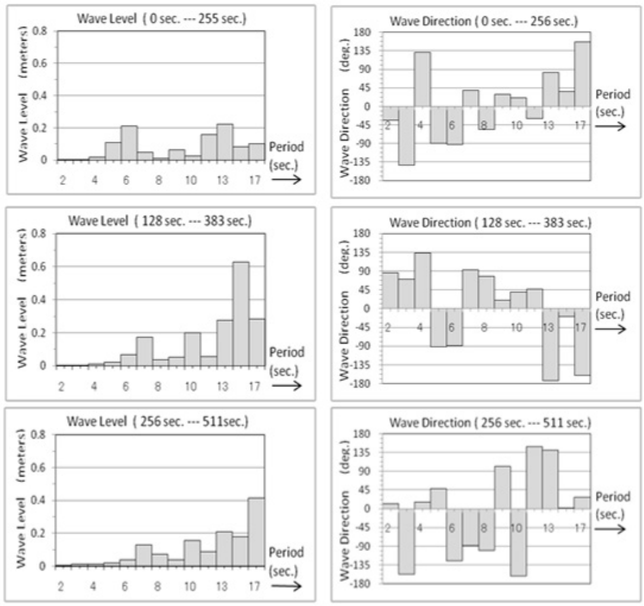

Figure 8. Solution of Wave Information

Figure 9 shows the time history of wave spectrum for approximately 1,000 s, so it presents the trend of wave information.

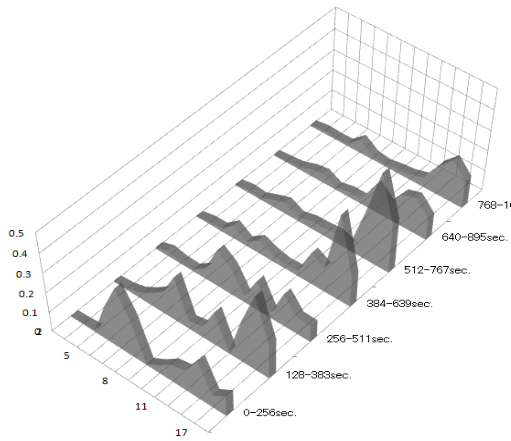

Figure 9. Time History of Wave Height

Summarize of the results of wave information is following:

1 In early time the wave of which period is 6 s and relative direction is -90 deg (true direction is 320 deg).
2 After (1) the true direction of the wave (*T*=7 s) is 080 ~ 130 deg.
3 The wave (*T*=6 s) and wave (*T*=7 s) fade out after approx. 600 s.
4 The wave (T=15 s) appears at 2nd duration (128 ~ 383 s) and 4th, the maximum level is 0.8 m and true direction is 030 ~ 045 deg.

The performance of onboard sensing wave information such as level and direction in these experiments is not able to be close investigated, but the possibility of onboard sensing wave information even during sailing because the trend of wave information sensed by this algorithm is reasonable which is wind condition (wind speed: 5 knots, direction: 165deg.), sea state is light breeze, and according to her sailing area the possibility of shadow effect of Peninsula Bousou.

5 CONCLUSION

The availability of Onboard Wave Sensing using VI-GPS is discussed and advanced algorithm is proposed to sense the wave effect.

According to the onboard experiments which show good results and possibility to sense wave effect on board, the possibility to achieve the measurement and application with a good solution of onboard sensing wave direction with the advanced algorithm and the performance of SDME required not only high accuracy but also high response and reliability are shown in this paper.

Onboard Wave Sensing system is also advantage to monitor the ocean wave using free-mooring buoy with VI-GPS.

Proceeding to develop this system, few points which should be resolved are following:

1 It is very difficult that absolute onboard evaluation would be done, but many cases should be surveyed, and gain the reliability of this system.
2 It is essential to review the response function of ship's motion because of reliability of wave information.
3 To apply the good performance of VI-GPS, one of which is a good response, so using a Gyrocompass, it takes care to exactly match timing.

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