Performance Requirement of Ship's Speed in Docking/Anchoring Maneuvering

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Abstract

Questionnaire survey on performance requirement of ship's speed such as not only accuracy but also response and robustness were carried out, and the experiments to survey the GPS performances of static and dynamic characteristics were carried out simultaneously. In this paper, the questionnaire survey focusing on docking maneuvering, some analytic results of the survey, the results of GPS performance, and the possibility of adaptation for docking maneuvering on SDME and GPS are discussed. Consequently, from the results of questionnaire survey the performance requirement of ship's speed in docking/anchoring maneuvering have need under 1cm/sec on the standard deviation, and speed information from GPS was adopted to use maneuvering information in docking/anchoring.

Keywords: Ship's Speed, Two Axes Velocity, Docking, Maneuvering, GPS, VI-GPS

1. Introduction

Since the latter half of 70's, Doppler Docking SONAR that is able to present three axes velocities (fore/aft movement and side movements at bow and stern) over ground within very high accuracy or 1cm/sec is applied to maneuver very large vessels such as VLCC. On the other hand, Docking Speed and Distance Measurement Equipment (SDME) had been also developed, that was usually installed on the dolphin alone and the docking speeds and distances at bow and stern were presented to ship and shore side. Recently due to the sonic disturbance, this Docking SDME on dolphin is developed with application of a laser instead of an underwater ultrasonic. It is frequent and effective for the VLCC to apply speed information to maneuver adequately and safely. Therefore, it was recommended that the two axes SDME should be fitted out more than 50,000GT in 2000SOLAS[1, 2]. On the other hand, for usual navigator of standard size vessels or less, it is not generally to make use of their precise speed. Sometimes their navigators caused the collision with dolphin or pier and affected his workload to heavy.

One questionnaire survey on performance requirement of ship's speed such as not only accuracy but also response and robustness was carried out. Many navigators specialized in maneuvering their vessels in the harbor were selected as questionnaire subjects and the some results of the questionnaire survey were analyzed by some statistical methods. Simultaneously the experiments to survey the GPS performances of static and dynamic characteristics were carried out.

In this paper, firstly an outline of the questionnaire survey is described focusing docking maneuvering, some analytic results of the survey are discussed, secondly the results of GPS performance are discussed, and finally the possibility of adaptation for docking maneuvering on SDME and GPS are discussed. Consequently, some recommendations to use the ship's speed adequately concerning docking maneuvering are described.

2. Speed Information in Docking Maneuvering

2.1 Questionnaire Survey

The questionnaire survey was conducted to the captains of ocean and domestic vessels of various ships' type in July 2006, and the collection rate was approximately 40%.

Object navigators and their vessels are shown in Table 1 and 2.

Table 1 License and Ship's Size Relations.

Ship's Size (GT) / License	~ 500	~ 3,000	~ 5,000	~ 10,000	~ 50,000	50,000 ~
1st grade	0	1	2	8	6	10
2nd grade	0	1	3	2	0	0
3rd grade	3	4	11	5	3	0
4th grade	2	3	0	0	0	0
5th grade	11	0	0	0	0	0
Total	16	9	16	15	9	10

Table 2 Ship's Type and Size Relations

Ship's Size (GT) / License	~ 500	~ 3,000	~ 5,000	~ 10,000	~ 50,000	50,000 ~
Tanker	0	2	9	0	0	4
LPG tanker	0	1	0	0	0	4
Container ship	0	0	0	0	0	0
Cargo ship	13	1	3	6	0	0
PCC	0	0	1	1	4	0
Tug	3	0	0	0	0	0
Ferry	0	4	1	2	4	0
Others	0	1	3	6	1	2
Total	16	9	17	15	9	10

2.2 Docking Maneuvering Procedures

Although maneuvering at quay and pier is divided into docking and leaving, our discussions focus on docking maneuvering.

2.2.1 Kind of Berth

The relation between the ship's size and the kind of berth, which the ship is docking, is shown in Fig. 1.

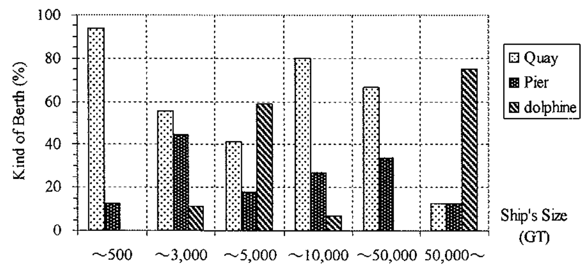


Fig.1 Kind of Berth

2.2.2 Maneuvering Procedures

The items on the docking maneuvering procedures in questionnaire are as follows, and Fig.2 shows the results of docking maneuvering procedures.

A: Approaching at a fixed angle toward a pier with engine, and docking alongside a pier with mooring fore and stern lines.
B: Turning stern with anchor, and docking pier from stern.
C: Slowing down with astern engine, and docking with lines and with or without bower anchors.
D: Slowing down with astern engine and docking from bow without a line.
E: Slowing down with astern engine and docking from bow with bower anchors.
F: Maneuvering with anchors.
G: Maneuvering with tugs.

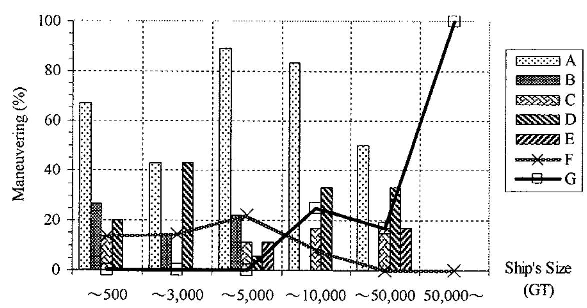


Fig.2 Maneuvering Procedure

The following features were found out from the obtained results.

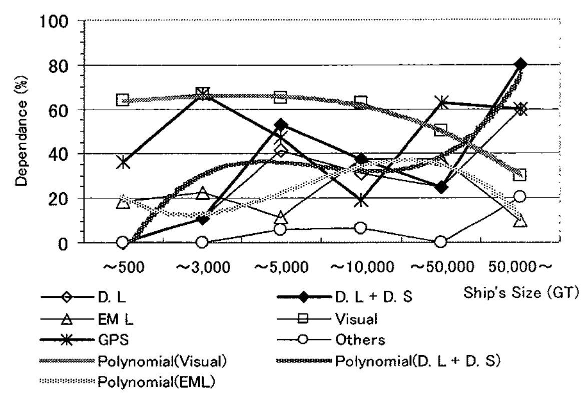
(a) Most of the vessels 3,000GT or more are maneuvering in the procedures A and C. Navigators of the vessels less than 3,000GT docking from bow or stern is remarkable. Moreover, nearly half are maneuvering in the procedure of A and C.
(b) The navigators of the vessels (500 to 3,000 GT and 10,000 to 50,000 GT) have little docking from alongside like the procedure of A and C. There are some cases docking from bow, because there were many samples of ferries.

2.3 Subjective Speed Information

2.3.1 Dependence on Speed Information

In various situations, on which measurement speed or velocity instruments it depended was classified by ship's size. The obtained results are as follows, and show the results in Fig. 3.

(a) Most navigators of the vessels less than 500GT do not depend on the Doppler Log and the Doppler Sonar. However, closer to 30 – 40% of navigators of the vessels from 3,000 to 50,000 GT depends on the Doppler Log and the Doppler Sonar, and 80% of navigators of the vessels 50,000GT or more depend on the Doppler Log and the Doppler Sonar.
(b) The dependence to visual or an E.M. Log is decreasing by navigators of the vessels 10,000GT or more, as shown also in Fig. 3.
(c) Approximately 50% of the navigator is dependent on GPS regardless of ship's size.
(d) A ship's size becomes larger, the more a navigator's dependence to two or more instruments increases.
(e) 58% of navigators always use speed measurements in docking.
(f) Most navigators of tanker, LPG, PCC and RORO are using speed measurements in docking.
(g) Navigators of tug rely on intuition without using speed measurements in docking.



The polynomial lines are smooth cubic curves.

Fig.3 Dependence on Speed or Velocity Instruments

2.3.2 Required Subjective Accuracy

Required accuracy on speed or velocity was classified by each ship's size.

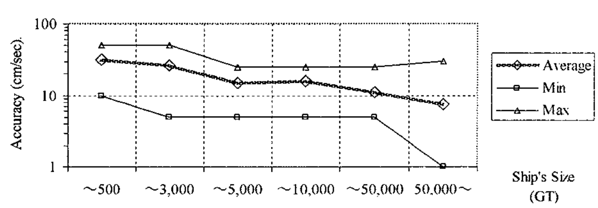


Fig.4 Required Accuracy on Speed or Velocity

2.3.3 Kind of Speed Information

The features about the necessity of SOG (Speed Over Ground) or STW (Speed Through Water) are as follows, and show the results in Fig. 5.

(a) Almost all navigators need SOG.
(b) Some navigators of the vessels less than 3,000GT need STW.

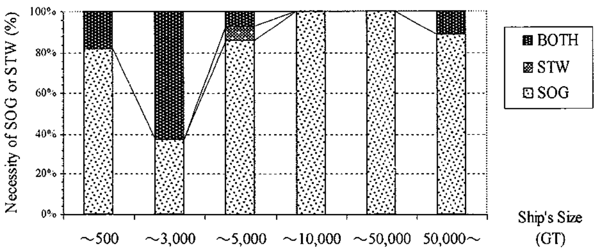


Fig.5 Necessity of SOG or STW

2.3.4 Measuring Point

The features about the measuring points are as follows, and show the results in Fig. 6.

- (a) The ship's size becomes larger, the more the necessity for the speed mainly concerned with fore/aft movement is increasing.
- (b) In the navigators of the vessels 50,000GT or more, the measurement of side movements is indispensable.
- (c) In the navigators of the vessels less than 50,000GT, the majority are ferries, and need speed information on fore/aft movement because the procedure for docking from bow.
- (d) Although it has decreased that the navigators of the vessels less than 50,000GT need for speed information on the whole of them, a part of them have necessity of measurement at not only fore/aft movement but also side movements.
- (e) Speed information of side movement at stern in docking has 2 to 3 times to demand compared with side movement at bow or fore/aft movement.
- (f) PCC, tug, cargo and ferry have many demands of speed information of side movement at stern. On the contrary, LPG has many demands of speed information of side movement at bow. These reasons relate the position of the bridge, and there are thoughts to demand side movement in a place left from the bridge.

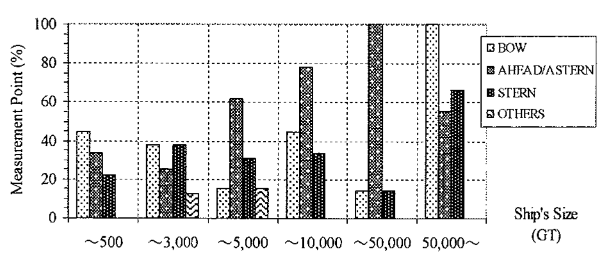


Fig.6 Measuring Points

2.4 Requirement Performance of Speed Information

2.4.1 Subjective Requirement

The result of the questionnaire obtained in section 2.3 is analyzed, therefore the navigator's subjective requirement is brought together as follows.

(1) Dependence on Speed Measurements Use in Docking

In section 2.3.1, it is clear that the navigators of the vessels 50,000GT or more need speed measurement. 30 to 40% of the navigators of the vessels 3,000GT or more a less than 50,000GT need speed measurements. Even the navigators of the medium ships need the docking speed though it depends on the kind of ship.

(2) Measuring Point

In section 2.3.4, the measurement place and direction of a docking speed are summarized. Moreover, in section 2.3.2, docking procedures are summarized. These sections show that many navigators of the small ships are also contained and need the speed information on side movement in the docking maneuvering procedure A.

(3) Accuracy of Speed Measurements

Although navigators of VLCC are requiring 1cm/sec, there is variation in demands in other kinds. Although requirement of subjective accuracy are appropriate as a general trend, the accuracy of the conventional speed measurements are imagined to influence greatly.

(4) Kind of Speed Information

Although navigators need SOG as a natural result, some navigators of the vessels less than 5,000GT need STW or both. Although this factor is not certain, it is considered as a possibility that the input to ARPA must be set to STW.

(5) Measurement Time Interval

Most navigators are answered 1 second or a moment in the result of the questionnaire though it does not describe in section 2.3.

(6) Reliability

Although not shown in sections 2.2 and 2.3, 76% of navigators have satisfied the present speed measurements from the questionnaire result. As satisfied reasons, the answer "An almost accurate SOG (Speed Over Ground) is obtained by using GPS" stood out.

However, 17% of the navigators are not satisfied. As dissatisfied reasons, there were answers such as "Velocity display of Doppler Log is out of order by the wake caused by propeller and/or tug", "It is not accurate", "Because the display was set on no good position, it is not possible to monitor", etc.

2.4.2 Systematic Requirement

It is necessary to protect a hull, a berth and passengers and/or cargo from damage of shock in docking. Therefore, the navigators should monitor the speed's information. It is required that speed or velocity of fore/aft and side movement should be high accuracy for safety maneuvering.

In the view of the accuracy of the SDME, the target docking velocity (D.V.) should be set, and monitoring D.V., the readout value include error shows as follows.

$$\text{(target D.V.)} + \text{(Margin)} < \text{(limit D.V.)} \quad (1)$$

$$\text{(readout D.V.)} \pm \text{(Error)} = \text{(target V.D.)} \quad (2)$$

$$\text{(readout D.V.)} < \text{(target D.V.)} - \text{(Error)} \quad (3)$$

The limit D.V. is set from designed limitation D.V. to protect a birth from shock in docking in VLCC and the margin should be set from the consideration of uncontrollable force such as wind effect, wave, current force, etc.

Considering application of SDME, its error should be within the range satisfied Equation (3) and the response also should be required to maneuvering in docking.

We discuss not only accuracy but also response and the relationship between them.

(1) Accuracy

Considering accuracy of SDME, we discuss the random error of which standard deviation is σ with sampling time T. According to make high accuracy, it is often to take the method of moving average with time constant T_K.

Suppose that the random error follows normal distribution, and then event that measurement value is within the velocity error U_a has the probability by integer N.

$$U_a = N\sigma / \sqrt{T_K / T} \quad (4)$$

(2) Response

The maximum acceleration of each ship was calculated from the database of the crash astern stopping time.[4] T_{ES} is the crash astern stopping time. K and n are driven from the database with parameter $V_o \Delta^{n/3}$, and V_o is initial speed in MCR; Δ is displacement (tons).

$$T_{ES} = K\Delta^{n/3} / V_o^n \tag{5}$$

The maximum acceleration $a_{\max}$ is conducted as follows.

$$a_{\max} = V_o / T_{ES} = V_o^{n+1} / (K\Delta^{n/3}) \tag{6}$$

The nominal mass of fore/aft movement is smaller than that of side movements. The latter is approximately twice of the former. When examining whether the time delay of a SDME affects accuracy, the difference of measurement values and real values should just be less than target values to the ramp response in the maximum acceleration of a movement system. U_r is the error caused by the response or time lag T_K of SDME and shows as follows.

$$U_r = \left| a_{\max} t - \frac{1}{T_K} \int_{-T_K}^{t} a_{\max}\, t dt \right| = \left| \frac{a_{\max} T_K}{2} \right| \tag{7}$$

(3) Trade-Off between Accuracy and Response

As mentioned above, there is a trade-off between accuracy and response of SDME. When movement is slow and accuracy is highly required, it is able to set the average time longer and make higher accuracy. In case of high movement, the average time should decrease until the limit of accuracy.

The error probability is 0.0007% in case of N = 4. This means that one or no miss-readout will occur in 4 hours when measurement value includes the error more than U_a. Integer N affects the accuracy of system, in SDME we discus setting N = 4.

3. Velocity Information from GPS

3.1 Velocity Integration Method [4, 5]

The observation equation for the GPS carrier phase measurements is as the following:

$$\Phi = \rho + c \cdot (dt - dT) + \lambda N - d_{ion} + d_{trop} + \varepsilon_{\delta\Phi} \tag{8}$$

Time differential observations are obtained by subtracting the observations at the previous epoch k-1 from those at the present epoch k. When the interval of observations is short, it is assumed that variations of propagation errors in the ionosphere and troposphere are small and negligible. The time differential observation is expressed in the following equation and temporal differences remove the phase ambiguities.

$$\delta\Phi = \delta\rho + c \cdot (\delta dt - \delta dT) + \varepsilon_{\delta\Phi} \tag{9}$$

Where ρ is the distance between satellite and receiver (m); c is the light velocity in vacuum (m/sec); Φ is the carrier phase measurement (m); λ is the carrier wavelength (m); N is the integer carrier phase ambiguity; d_{ion} is the bias of the ionospheric delay (m); d_{trop} is the bias of the tropospheric delay (m); dt is the bias of the satellite clock (sec); dT is the bias of the receiver clock (sec); $\delta\Phi$ is the phase observation in temporal difference between two epochs (m); δdt is the variation of the satellite clock errors (sec); δdT is the variation of the receiver clock errors (sec); $\varepsilon_{(*)}$ is the measurement noise and the errors which cannot be modeled and the symbol δ is the time differential operator. Observations at a 1sec interval give a solution for unit displacement, *i.e.* velocity.

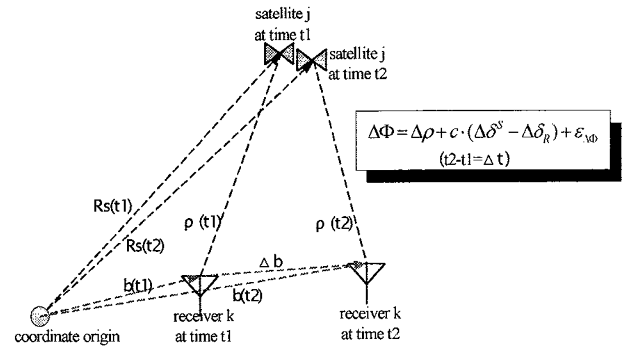


Fig.7 Time differential carrier phase measurement

3.2. Experiment

3.2.1 Outline of Experiment

GPS experiment was carried out on 24th and 25th of July in 2006. One GPS antenna as a reference station was fixed on the roof of Kobe University Faculty of Maritime Sciences No.2 Building, and another GPS antenna was equipped with 3D movable body used to evaluate an accuracy of GPS speed information. Fig.8 shows the 3D movable body and GPS antenna. In our experiments, two speeds of movable body by the K-GPS and VI-GPS were compared statically, and a step response and accelerated motion were tested dynamically. In our all experiments, the sampling frequency was selected 5Hz.

In square experiment, one side length is 70cm, and there are three speeds that are 1cm/sec, 5cm/sec, 10cm/sec respectively. Each square experiment had about 300sec data length. In circle experiment, the diameter was selected 70 cm, and the liner speed was 20 cm/sec. Two square experiments had about 3600sec data length.

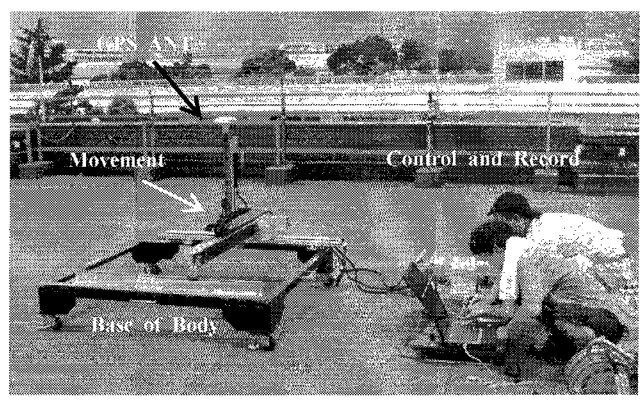


Fig.8 3D movable body and GPS antenna

3.2.2. Static Results

Table 3 and 4 show two experimental results of the speed by the VI-GPS. In Table 3, every average (Av) results hold about the same speed of the movable body, and standard deviations (σ) increase with the speed of the movable body. The percentage error of average speed keeps under 6 %.

The time length of the experimental results of circle test was long, then the circle data were divided into three average values of HDOP. In Table 4, every average (Av) results hold about the same speed of the movable body, and each standard deviation (σ) are uncorrelated with PDOP value, and are under 4%. The percentage error of σ keeps under 4%.

From the static results, the average information of ship's speed by VI-GPS keeps under 6%, and the σ of it holds under 1.03cm/sec at most. Especially, σ under 5cm/sec is restricted under 0.5cm/sec, then it is considered that speed information by VI-GPS is evaluated as very useful and effective information in docking and anchoring the ship.

Table 3 Experimental results of square test by VI-GPS

		Direction (deg.)					
1cm/sec		0	15	30	45	60	75
Speed (cm/sec)	Av	1.06 (6)	1.00 (0)	1.01 (1)	1.01 (1)	1.02 (2)	0.99 (1)
	σ	0.30 (30)	0.26 (26)	0.23 (23)	0.24 (24)	0.25 (25)	0.27 (27)
5cm/sec		0	15	30	45	60	75
Speed (cm/sec)	Av	4.92 (2)	4.90 (2)	4.94 (1)	4.88 (2)	4.92 (2)	4.89 (2)
	σ	0.47 (9)	0.42 (8)	0.45 (9)	0.61 (12)	0.51 (10)	0.67 (13)
10cm/sec		0	15	30	45	60	75
Speed (cm/sec)	Av	9.63 (4)	9.67 (3)	9.67 (3)	9.64 (4)	9.68 (3)	9.66 (3)
	σ	1.03 (10)	0.92 (9)	0.95 (10)	0.96 (10)	0.96 (10)	0.98 (10)

The value in parentheses means percentage error.

Table 4 Experimental results of circle test by VI-GPS

26th of JULY, 20cm/sec		2=<DOP	2<DOP<3.0	DOP>=3.0
	Av. PDOP	1.92	2.73	3.11
Speed (cm/sec)	Av	19.8 (1)	19.8 (1)	19.8 (1)
	Σ	0.44 (2)	0.38 (2)	0.38 (2)
27th of JULY, 20cm/sec		2=<DOP	2.0<DOP<3.0	DOP>=3.0
	Av. PDOP	1.9	2.77	3.11
Speed (cm/sec)	Av	1.98 (1)	1.98 (1)	1.98 (1)
	σ	0.71 (4)	0.41 (2)	0.37 (2)

The value in parentheses means percentage error.

3.2.3. Dynamic Results

We have two kinds of dynamic test. One is a step-response that was used to evaluate a time response of the speed change by VI-GPS. At the beginning of this experiment, the 3D movable body was stopped, and next it was moved at a rate of 0.3G. Finally it was moved at a constant speed of 10cm/sec. The other is acceleration test that is used to the static test results of circle. In circle static test, the acceleration to X axis changes like a sine wave, and the acceleration to Y axis changes like cosine wave with a 180 degrees phase lag. Then to compare two accelerations to X and Y axis, the acceleration change from 0 to 15 cm/s^2 can be evaluated.

Fig.9 shows the results of three step-responses by K-GPS and VI-GPS. In this figure, a dotted line is K-GPS speed that is difference of two sequential positions every 0.2sec, a black bold line is K-GPS speed that is difference of two sequential positions every 1sec, and another bold (red) line means VI-GPS speed that is measured by the velocity integration method every 1sec. From these results, a step-response by K-GPS (0.2sec) has no time lag for the input signal, but K-GPS (1sec) and VI-GPS (1sec) have about one second lag from 0 to 10 cm/sec because of the smoothing process. Then if we can get VI-GPS (0.2sec), it is considered that there is no time lag of VI-GPS, but a variation of measured speed become large.

The results of raw speed by K-GPS (0.2sec) had an overshoot phenomenon in step-response, because the GPS antenna had possibility of a characteristic vibration due to the coupling rod between the GPS antenna and the 3D movable body. Consequently, it is considered that the 10cm/sec was larger than another speeds as in the static results is caused by the characteristic vibration of coupling rod.

Fig.10 shows the results of the acceleration test. From the results of this figure, two accelerations to X and Y axis present accurate changes of acceleration from 0 to 15 cm/s^2. Consequently, ship's speed information by VI-GPS has no time lag with K-GPS, and acceleration information by VI-GPS show a stable change up to 15cm/s^2. Then it is considered that acceleration information by VI-GPS is evaluated as very useful and effective information in docking and anchoring the ship.

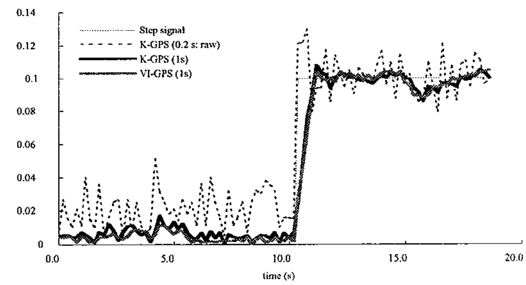


Fig.9 Step-response by K-GPS and VI-GPS

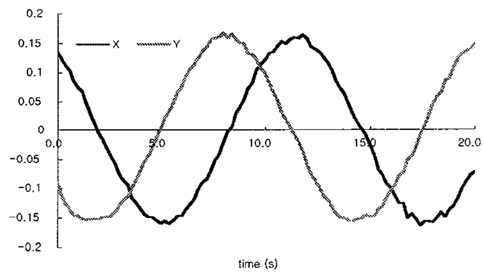


Fig.10 Acceleration change of circle test

4. Discussion on the Performance of Velocity Information

It is said that the limit of designed docking velocity is decided from protection of a birth or a dolphin, and the typical one for sea-berth in the case of 200,000DWT VLCC is between 12 and 15 cm/sec.

In the case of real docking, it is said that the limit of designed docking velocity for 10,000DWT conventional cargo ship is 10cm/sec, one for 80,000DWT – 90,000DWT type ship is 2cm/sec – 8cm/sec and one for 200,000DWT – 300,000DWT VLCC is 1cm/sec – 5cm/sec.[6]

In this chapter, we discuss the required performance on the velocity in docking maneuvering according to the data described above. It is very important to discuss the dynamic performance of the speed or velocity information applied to vehicles' maneuvering even to the ship's maneuvering. There is no discussion on response of SDME or GPS's speed information.[7] In SOLAS the carriage requirement is decided based on gross tonnage, but the response of ship's movement relates to the ship's displacements.

The response or time lag of velocity measurement equipment also should be discussed based on the relationship of trade-off between accuracy and response, which are described at section 2.4.

4.1 Accuracy and Response of Doppler Sonar

In case of Doppler Sonar, it is said that its error at low speed is within 1cm/sec and taking account of the trade-off between accuracy and response of ship's movement such as VLCC the velocity information is averaged with averaging time 8 sec.[8]

It is possible that the dynamic random error in theoretical is $1cm/sec/Hz^{1/2}$, but on board its accuracy will decrease according to the reduction of signal level, etc. Therefore, we calculate the effect of trade-off in Doppler Sonar supposing that its dynamic random error is $2cm/sec/Hz^{1/2}$.

In case of VLCC, the limit of D.V. and target D.V. is 15cm/sec and 5cm/sec, so it is possible that the margin of docking velocity should be set 10cm/sec. Then, we got the result of the safety reading velocity of Doppler Sonar at docking within 1cm/sec in the example of 300,000DWT VLCC using formulas described in section 2.4.2.

4.2 Accuracy and Response of VI-GPS

In this section, we calculate the reliability of reading using VI-GPS described in Chapter 3 in the case of 300,000DWT VLCC. The dynamic random error got from experience is approximately 1cm/sec/Hz. If we request 99.99% reliability in reading, then 4σ of VI-GPS with average time 1sec is same as the case of Doppler Sonar. It is possible that average time is set more than 1sec. Setting average time 4sec, safety reading D.V. is 2cm/sec. The trade-off between accuracy and response of VI-GPS in case of 300,000DWT VLCC is shown in Fig.11.

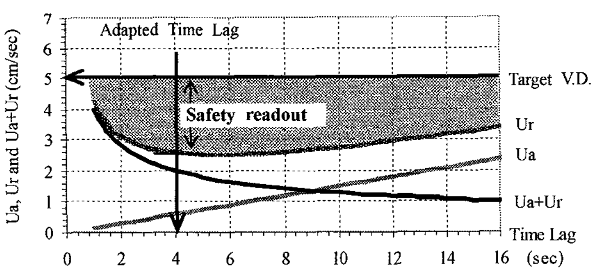


Fig.11 Trade-Off between Accuracy and Response in VI-GPS

4.3 Effect of Ship's Size

The limit of designed docking velocity is affected by the ship's size and the structure of berth described in section 2.4, so we calculate trade-off in cases of different ship's size and Fig.12 shows the relationship of the performance for Doppler Sonar and VI-GPS.

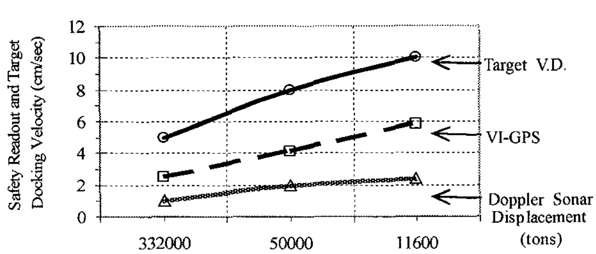


Fig.12 Safety Readout of Docking Velocity

Fig.12 shows that both instruments are possible to apply docking maneuvering for three ship's size vessels 300,000DWT, 50,000DWT and 10,000DWT, and that the safety readout on VI-GPS is larger than the safety readout on Doppler Sonar.

It trends that the safety readout increases as ship's size as smaller. This means that it is easy to apply readout for not only VLCC but also less than large vessels because maneuvering velocity range increases.

We conclude that there is possibility to apply VI-GPS for docking maneuvering with high response same as or more than Doppler Sonar, especially in small ship's size.

5. Conclusion

In this paper, the subjective performance requirement from questionnaire survey, systematic study on adaptation of SDME for docking maneuvering, the result of experience on GPS performance and possibility on the adaptation of GPS are discussed and presented.

We conclude that;

- Vessels less than 50,000GT need two axes SDME in docking according to the questionnaire survey.
- Both performance accuracy and response of SDME need in order to keep high accuracy for the safety docking maneuvering.
- Survey on static and dynamic VI-GPS performance showed that the random error is 1cm/sec with the moving average time 1sec when HDOP is less than 3.
- The possibility of adaptation on VI-GPS for docking maneuvering is better than conventional SDME because of poor response.

We will proceed our research focusing two point as follows; (1) systematic survey on the performance requirement for small vessels, and (2) robustness of VI-GPS not only HDOP but also integrity and multi-pass.

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