Measurement and Estimation of Waves Generated by a Small Ship in Port

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Abstract- **Many theoretical studies on waves generated by relatively large ships have been done, and many design experiments have been undertaken to reduce wave resistance using models in a towing tank or a circulating water channel. However, little research has been conducted on waves generated by relatively small real ships. Occasionally, waves generated in the port by small ships traveling freely at high speeds cause severe sea conditions for moored loading ships, other small boat, and visitors on the pier. In particular, large waves generated in port by powerful tugboats can affect small boat in passing, moored small boats, yachts in marinas and yacht harbor, and people using recreational sea areas.**

The purpose of this paper is to discuss the experimental measurement of ship waves generated in port by powerful tugboat and other small boats at high speeds, and to examine the estimations of heights, periods and direction of ship waves.

I. INTRODUCTION

In an average port, both traveling and moored are a variety of vessels such as cargo ships, fishing boats, passenger boats, pleasure boats, and others. As ports can be rather crowded and the sea area is relatively narrow, the possibility is high for dangerous traffic conditions that can result in stranding and collisions. In addition, waves generated by ships can lead to dangerous conditions for other ships and port visitors. As powerful, high-horsepower tugboats and pleasure boats travel relatively rapidly in port, the waves generated can causes severe sea conditions for moored and traveled other ship, and fishing or pleasure visitors in the near pier of the port.

While a great deal of research has been conducted on ship wave resistance, waves generated in port by relatively small ships have not been well studied[1~4]. In an effort to prevent marine accidents, it is very important to examine waves generated in port by small ships such as tugboats and pleasure craft.

This paper addresses the characteristics of waves generated by small vessels in port. Specifically, waves generated by tugboats and pleasure boats were measured and estimated in Japan's Port of Kobe. Wave measurement was carried out by varying ship speed and distance between the wave height meter and the moving ship. As result of this research, it was found that the characteristics of ship waves were understood and the estimation of the wave height, wave period and wave direction of ship waves were relative satisfactory.

II. MEASUREMENT OF SHIP WAVES

A schematic of the ship wave measurement area is shown in Figure 1. The observation of ship waves was carried out with an ultrasonic wave meter fixed to a stand at the quay. The wave height and period were obtained from the wave profile data.

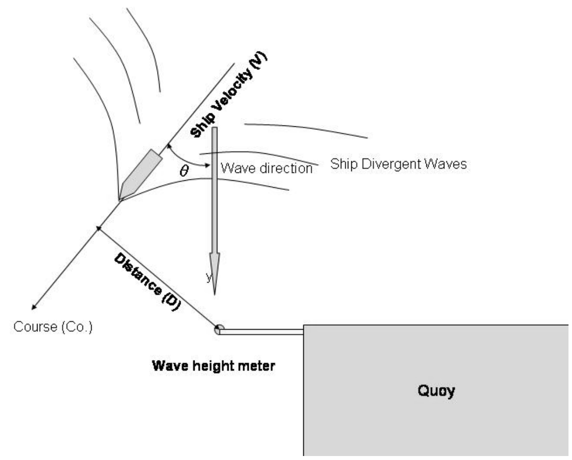

Figure 1: Schematic measurement conditions

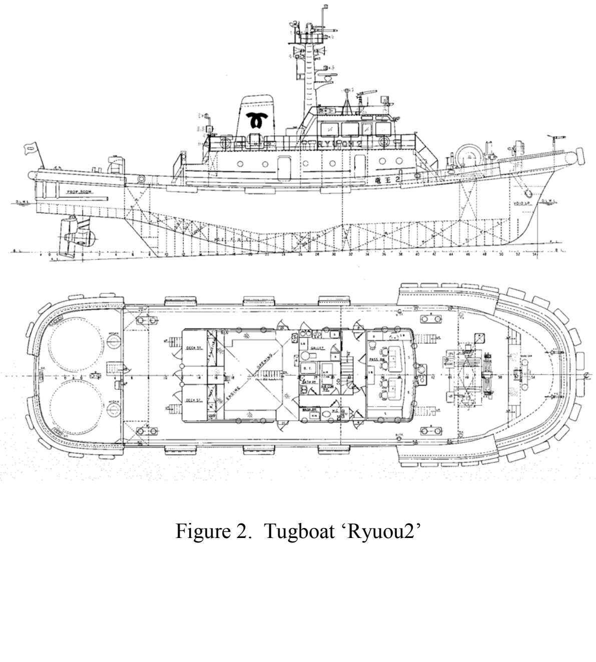

Figure 2. Tugboat 'Ryuou2'

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Table 1 Specifications of tugboats in the Port of Kobe

	G/T (ton)	LOA (m)	Lpp (m)	B (m)	D (m)	Draft (m)	Speed (knot)	Bollard Pull (Max) (tonf)	Main Engine Type	B.H.P. (PS)	B.H.P (kW)
A	198	34.0	29.0	9.2	4.18	3.0	13	55	Z280-EN	D 3600PS x2	2647
B	197.8	31.0	27.0	8.8	3.49	2.7	12	36	—	D 2600PS x2	1911
C	196.0	31.0	27.0	8.8	3.48	2.6	12	36	—	D 2600PS x2	1911
D	195	33.5	29.5	9.2	4.18	3.2	13	45	6DLM -28S	D 3600PS x2	2647
E	158	30.8	26.4	8.6	3.78	2.6	13	37	6N21A -EV	D 2600PS x2	1911
F	153	30.8	25.5	8.6	3.80	2.7	13	35	—	D 2600PS x2	1911
G	191	33.4	31.5	9.2	4.00	2.6	14	48	6L28HX	D 3600PS x2	2647
H	153	31.5	29.7	8.6	3.75	2.0	12	40	6L25CXE	D 2600PS x2	1911
I	161	31.5	26.1	8.6	3.80	2.7	13	42	6L25HX	D 2600PS x2	1911
J	193	33.3	29	9.2	4.17	3.2	14	50	Z280-EN	D 3600PS x2	2647
K	152	30.8	25.5	8.6	3.78	3.2	13	36	6L25BX	D 2600PS x2	1911
L	154	30.3	25.8	8.6	3.77	2.7	12	36	6L25BX	D 2400PS x2	1764
M	199	33.0	28.5	9.2	4.183	3.1	14.	50	6L28HX	D 3600PS x2	2647
N	160	30.9	26.0	8.8	3.78	2.7	12	36	6L27.5X	D 2600PS x2	1911
O	164	30.9	26.0	8.8	3.78	2.7	12.3	36	6L27.5X	D 2600PS x2	1911
P	193.67	28.4	25.0	8.5	3.48	2.6	11	30	8PSHTcM -26D	D 2100PS x2	1544
Q	195	33.9	29.5	9.4	4.00	3.1	14	52	6L28HX	D 3600PS x2	2647
R	195	34	29.9	9.2	4.20	3.2	14	—	Z280-FN	D 3600PS x2	2647
S	101.27	23	19.1	6.6	3.00	2.3	11	18	6L20AX	D 1300PS x2	955
T	157	31.5	26.5	8.6	3.78	2.6	13	36	—	D 2600PS x2	1911

Using functional craft, ship wave measurements were obtained in Japan's Port of Kobe. The experimental area is located in the inner reaches of Osaka bay and is surround to mole. In this area, neither large swells from the open sea nor wind-generated waves are present. During our experiments, the wind was very calm, and the sea was quite smooth. As a result, the effects of wind-generated waves and ocean swells were very minimal. The water depth in the area was approximately 20m, and the ship waves were regarded as deep-water waves.

Two kinds of craft were selected for experimentation: a tugboat and a pleasure boat. Powerful tugboats and fast-moving pleasure craft generate significant waves in port. Being common to most ports, these vessel types were ideal for

Table 2 Primary characteristics of tugboat Ryuoh2

Item		Item	
Gross Ton	194ton	Main Eng. (B.H.P)	1323kWx750min^{-1} x 2sets
L.O.A.	34.0m	Aux. Eng. (B.H.P)	118kWx1800 min^{-1} x 2sets
L.P.P	29.9m	Bollard P.	Fore 50.5t, Aft 48t
B(MLD)	9.2m	Max. speed	14.6kt
D(MLD)	4.2m	Propeller Unit	Azimuth drive propeller KST-180ZF/A x 2sets
d(Des.)	3.2m		

Figure 3 Pleasure boat Mukomaru

our study.

There are about twenty tugboat in the port of Kobe. As these boats were passing near the experimental area, the general characteristics of tugboat-generated waves were examined. Table 1 shows main item of tugboats in the Port of Kobe. Nearly all tugboats in the port are 150~200 gross tons, 35~50m in length, employ twin engines of 2600~3600 hp, and travel at a ship speed of 12~14 knots.

The tugboat "Ryuou2" was selected for a more detailed examination of the tugboat-generated wave characteristics. This tugboat is the standard model owned and operated by the Port Office of Kobe City. The tugboat used in the ship-wave experiment is shown in Figure 2, and the tugboat's specifications are listed in Table 2. The research tugboat is an ordinal displacement type and operates the general work.

This pleasure boat used in our study, an average model, is shown in Figure 3. The boat is generally used at Kobe University for training students in marine research and observation or maneuvering. The specifications of the boat are listed in Table 3.

The maximum wave height and corresponding wave period are obtained from the profile data measured by the wave meter. The maximum height of the ship waves was defined as the distance between the maximum ridge and the successive trough of waves. The wave period was defined as twice the time interval between the maximum ridge and the trough of the corresponding wave. The time interval for data sampling was 0.1s, and the length of the ship wave time series data was 100s. The wave direction was measured by reading a compass card, and wave's direction was defined by the angle between ship's course and the arrival direction of the wave's ridgeline (as shown in Figure 1).

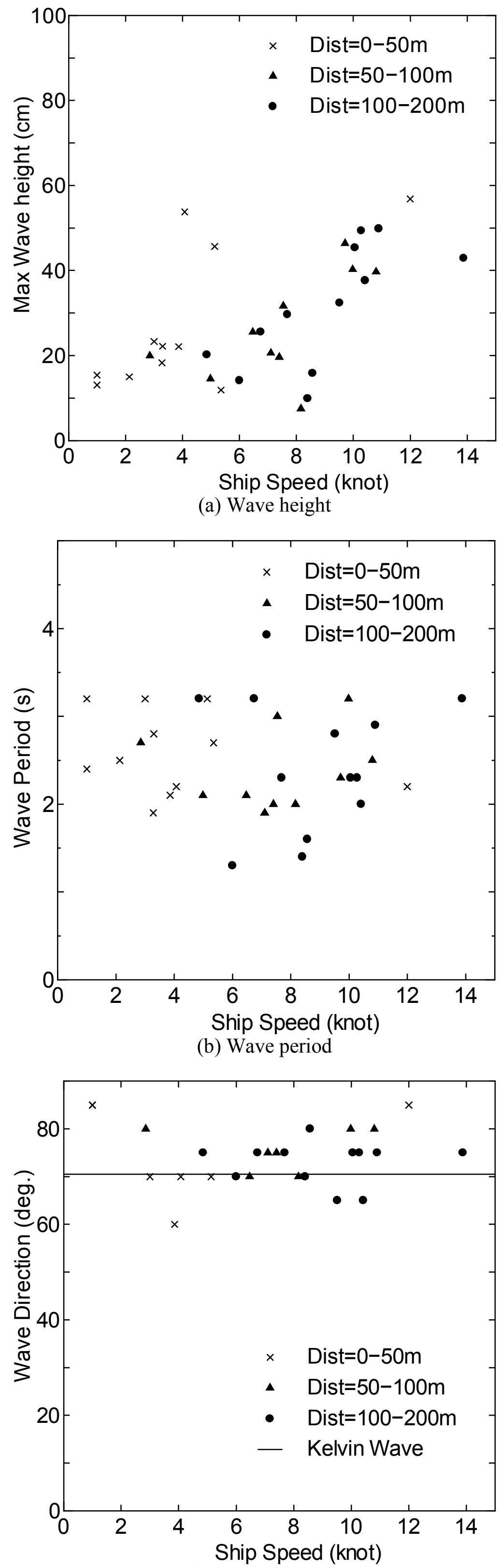
Measurements were taken while varying ship speed and maintaining a constant distance from the sailing line to the wave meter. In addition, distances were varied while maintaining a constant speed. Ship speed was measured by timing the duration required to pass a fixed distance between two poles installed on the quay. An onboard laser distance meter was used to determine the distance between the sailing line and the wave meter.

Ⅲ. ESTIMATION OF SHIP WAVES

The estimation of ship waves was carried out using a simplified calculation method. In practice, the case of this method, the height and period of the maximum wave were estimated utilizing simplified specific data, such as the tonnage, horsepower, and the principal scale of a ship.

The maximum height of a wave is defined as the maximum vertical distance between the successive ridge and trough of the waves. The wave period is defined as twice the time interval between the ridge and the trough of the corresponding wave. The maximum height of a ship wave can be estimated as follows:

$$H_{\max} = H_0 (100/s)^{1/3} (v/v_k)^3 \ , \tag{1}$$



(a) Wave height

(b) Wave period

(c) Wave direction

Figure 4 Waves of measured tugboats (speed variable) where

$$H_0 = (L/100)^{1/3}\sqrt{EHP_W / 2.2Lv_k} \quad , \tag{2}$$

H_0 (m) : maximum wave height at the parallel line 100m away from the sailing line,

v (knots) : sea speed at full engine load,

v_k (knots) : actual ship speed,

s (m) : distance from the sailing line,

L (m) : ship length,

EHP_w (HP) : maximum continuous horsepower,

which can be obtained by the following equations:

$$EHP_w = EHP - EHP_F\,, \quad EHP = C \cdot SHP_m\,,$$
$$EHP_F = (\rho/2)SV_0^2C_f(V/75), \quad V_0 = 0.514V, \tag{3}$$
$$C_f = 0.075/\sqrt{\log(V_0L/\nu) - 2}\,,$$

C : a coefficient taking 0.6175~0.7425,

SHP_m (HP) : shaft horsepower,

ρ : density of sea water,

C_f : frictional drag coefficient,

ν (m^2/s) : kinematic viscosity of sea water (=1.2×10^{-6}),

S : wet surface area

W (m^3) : full load displacement.

V: actual ship speed

The wave period corresponding to a ship's maximum wave height is calculated as:

$$T = T_0\cos\phi, \quad T_0 = (2\pi V/g), \tag{4}$$

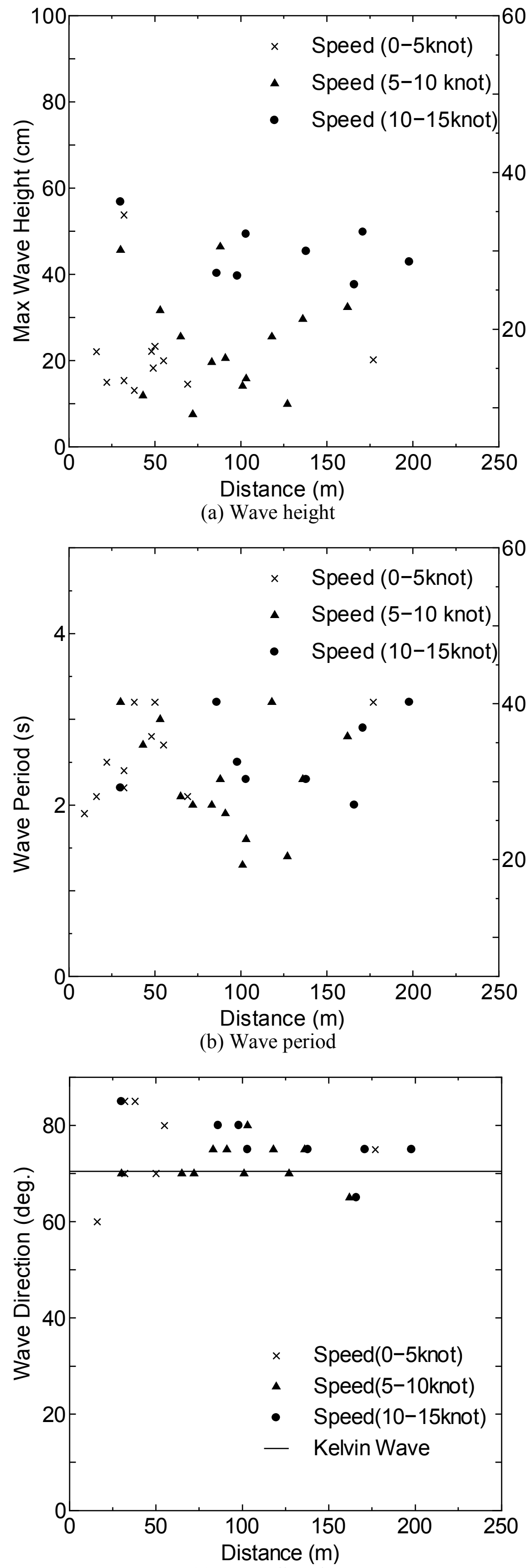
where g is the acceleration of gravity and φ is 35°16', which corresponds to the theoretical propagation direction of transverse waves obtained by Kelvin's ship wave theory.

The direction of ship's transverse waves was estimated using the hypothesis that the ship waves propagate in the same direction as the Kelvin wave,.

Ⅳ. MEASUREMENT AND ESTIMATED SHIP WAVES

A. General Characteristics of Ship Waves of Tugboat Waves in the Port of Kobe

Figure 4 shows the general characteristics of tugboat-generated waves in the Port of Kobe. In Figure 4, (a) shows maximum wave height, (b) is wave period corresponding to the maximum wave, and (c) is wave direction. Measurements of tugboat-generated waves passing parallel to the quay in the middle area of the Port of Kobe were carried out for four days. In the figure, the horizontal axis shows the speed of passing tugboats, and the vertical axis shows measured and estimated maximum wave height, wave period, and wave direction. As the distances from the sailing line of each passing ship to the wave meter vary, they were categorized into three sets of distances: 0-50m, 50-100m, and 100-200m. The maximum wave height increases proportionally to ship speed and decreases inverse-proportionally to the distance. As the maximum measured wave height is about 60cm and the wave height reaches twice in consideration of the composition with the refraction wave from the quay, the highest wave heights make dangerous conditions to other small boats[5].



(a) Wave height

(b) Wave period

(c) Wave direction

Figure 5 Waves of measured tugboats (distance variable)

The wave period distribution is scattered, and the wave directions are almost constantly in agreement with theoretical models.

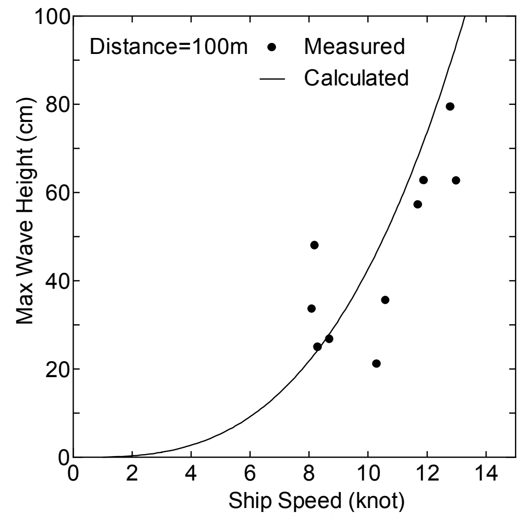
Figure 5 shows further characteristics of tugboat-generated waves in the Port of Kobe. In the figures, the horizontal axis shows the distance between the wave meter and the sailing line of passing tugboats, and the vertical axis shows the same as in Figure 4. As the speed of each passing ship is different, the measured ship speeds were categorized into three speed sets: 0-5, 5-10, and 10-15 knots. The maximum wave height decreases inverse-proportionally to the distance from the sailing line and increases proportionally to the ship speed. The wave period distribution is scattered, and the wave directions are almost constantly in agreement with theoretical models.

B. Detailed Characteristics of Ship Waves Produced by the Tugboat Ryuou2

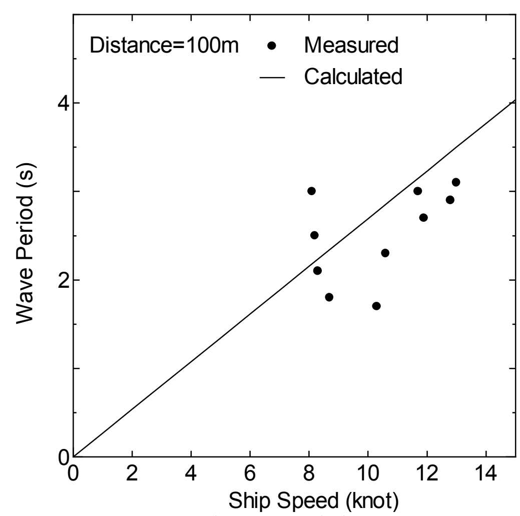
The examination of detailed ship wave characteristics produced by a specific vessel was carried out using the tugboat "Ryuou2." Wave measurements were carried out while varying the ship speed and maintaining the distance between the sailing line and the wave meter, and while varying the distance and maintaining a constant ship speed. The ship speed in the experiments ranged from 8 to 13 knots. As shown in Figure 1, in order to avoid waves reflected from the quay, the ship course was adjusted so that waves would be incident.

Figure 6 shows the comparison of experimental and estimated results of ship waves generated by Ryuou2 while varying the speed and keeping the distance between the sailing line and the wave meter at about 100m. In Figure (a), the real line is the calculated maximum wave height and the circle mark is the experimental result. The experimental results are scatter to be difficult to keep manoeuvrability of the tugboat in low speed. At the higher ship speeds, the calculated results are smaller than the experimental results. Though the experimental results at low ship speeds are scattered in Figure (b), both wave period results are proportional to ship speed. In Figure (c), the calculated wave direction is the constant, and the experimental results are similar to the calculated ones.

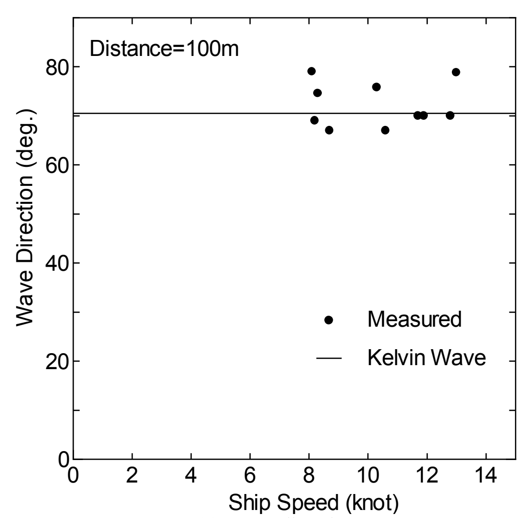
Figure 7 shows the comparison of experimental and estimated results of waves generated by Ryuou2 while varying the distance between the sailing line and the wave meter and keeping the ship speed at full speed (about 12.7 knots). In Figure (a), the maximum wave heights decrease inverse-proportionally to the distance. Though the experimental results are lower than the calculated results, both are relatively similar. In the experimental results, the maximum wave height at the distance of 100m is larger at about 80cm, and the wave height at the distance of 300m decreases to about 40cm. Therefore, increased distance from the sailing line results in a lower wave height and increases safety levels for other small boats. Though the measured wave periods are smaller than the calculated ones, both results are very similar. The measured wave directions are larger than the calculated ones at both



(a) Wave height

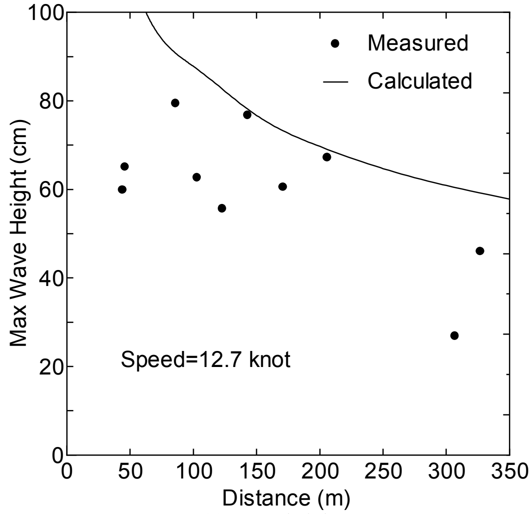


(b) Wave period

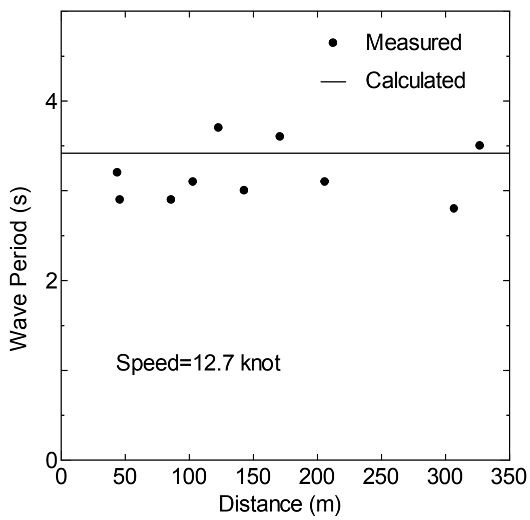


(c) Wave direction

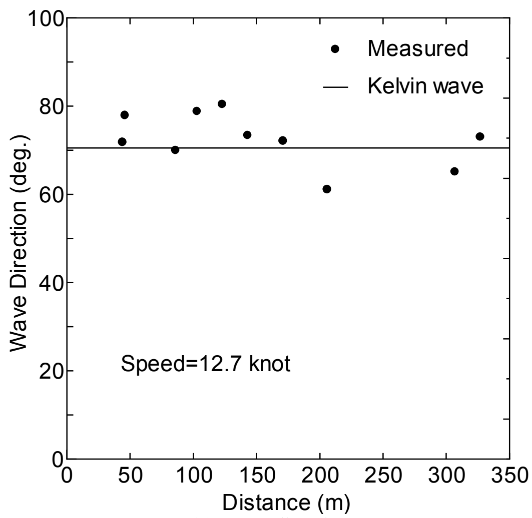
Fig.6 Waves of Ryuou2
(speed variable)



(a) Wave height



(b) Wave period



(c) Wave direction

Fig.7 Waves of Ryuou2
(distance variable)

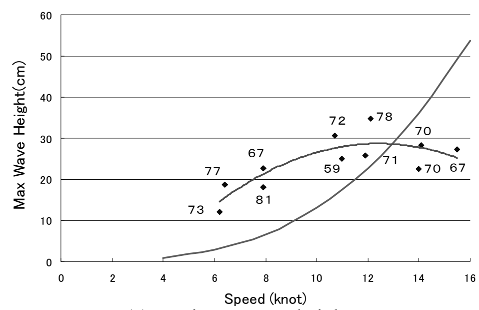
Photo. 2 Waves generated by Ryuou2

short and long distances. Both results are relatively similar. As a result, the simplified calculation method is satisfactory to estimate the characteristics of tugboat-generated waves.

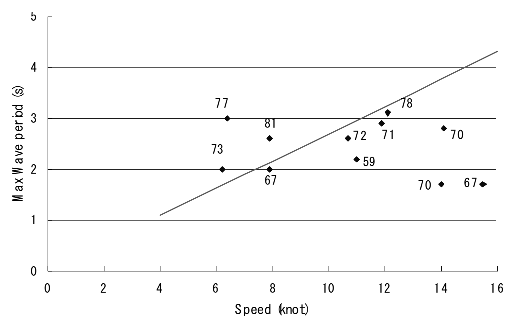
Figure 8 shows the profile of waves generated by the tugboat Ryuou2. The profile of waves nearest the hull shows breaking, and parts of the continuous wave are breaking as well. Therefore, the energy of ship waves gradually reduces as they move away, and the wave height decreases as a result.

C. Detailed Characteristics of Ship Waves Produced by the Pleasure Boat Mukomaru

A small pleasure boat was also used in the examination of ship waves. Wave measurements were carried out while varying the ship speed and maintaining the distance between



(a) maximum wave height



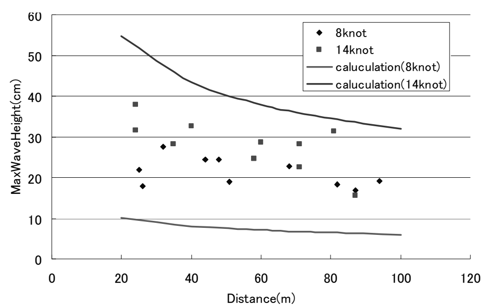
(b) wave period

Figure 9 Waves of Mukomaru
(speed variable)

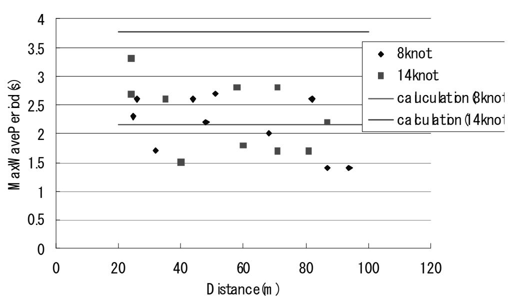
the sailing line and the wave meter, and while varying the distance and maintaining a constant ship speed. As with the tugboat experiments, the ship speed ranged from 8 to 13 knots.

Figure 9 shows the comparison of experimental and estimated results of waves generated by Mukomaru while varying the ship speed and keeping the distance between the sailing line and the wave meter at about 70m. Figure (a) shows the comparison of measured and estimated maximum wave height. In the figure, the real line is the calculated maximum wave height, the circle mark is the experimental result, and the dotted line is the approximated curve of the experimental results. In the range of lower ship speeds, the wave height increases proportionally to ship speed. However, the wave height decreases inverse-proportionally to ship speed in the range of higher speeds. In general, this tendency was not shown in the case of ordinary displacement type ships, as shown in Figure 4. Due to hull characteristics, pleasure boats traveling at higher speeds experience lift due to the planning phenomenon. As a result, the hydro-water volume of the boat decreases, and the volume of water displaced by the advancing craft decreases. Therefore, the simplified estimation process is not effective, and a new method will be needed in the future. In Figure (b) of the wave period, the experimental results are almost constant and are not proportional to the ship speed as shown in Figure 4 (b).

Figure 10 shows the comparison of experimental and estimated results of waves generated by the small boat Mukomaru while varying the distance between the sailing line and the wave meter and keeping the ship speed at about 8 and 14 knots. Figure (a) shows the height of the ship waves. In Figure (a), the measured results decrease inverse-proportionally to the distance, and the wave heights tend to be in agreement with the calculated results. However, due to hull planning, the measured results in the case of a higher ship speed (14 knots) are considerably smaller than the calculated ones. In Figure (b), the measured wave period are nearly constant in the case of this region of experimental distance.



(a) maximum wave height



(b) wave period

Figure 10 Waves of Mukomaru
(distance variable)

As a result of these experiments, due to hull planning, the maximum wave height produced by the pleasure boat decreases at higher speeds. For the purpose of reducing wave heights, decreasing ship speed is need in the case of a displacement-type ship. Conversely, in the case of pleasure craft, increasing ship speed may be effective for decreasing wave height.

V. CONCLUSION

The examination of the height, period, and direction of waves generated by the tugboat and the pleasure boat in the Port of Kobe was carried out through estimation and experimentation in real-world sea conditions. The characteristics of ship waves were obtained in the experiments, and a simplified method for estimating general wave characteristics was proposed. In case of displacement-type craft, i.e., a tugboat, this method is very effective and produced results in agreement with those obtained in field experiments. However, this method is not effective for pleasure boats traveling at higher speeds. This is due to the fact that, at higher speeds, the hull of pleasure boats generates lift through the planing phenomenon, and the hydro water volume of the boat reduces. As a result, the wave height decreases.

As the characteristics of ship waves were obtained by the field experiments of measuring the ship waves, it is possible to keep the navigational safety in Port by avoidance of dangerous by the waves generated by these ships

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