CHAPTER TWO HUNDRED EIGHTEEN

SHIP WAVES IN SHALLOW WATER AND THEIR EFFECTS ON MOORED SMALL VESSEL

by

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ABSTRACT

The characteristics of ship-generated waves in shallow water and the motions of moored small vessel induced by the ship waves were investigated in a wide range of water-depth and ship-length Froude Numbers.

The maximum heights and periods of ship waves were obtained as functions of Froude Number. The relationships between maximum angular and translatory displacements of moored vessel and the maximum ship waves were determined.

INTRODUCTION

The waves resulting from passages of ships have relatively large heights compared with their lengths, and hence the surface slopes of ship-generated waves are steep so as to cause large motions of small vessels moored at the structures adjacent to waterways such as wharves, quays and piers.

Since the pioneer's work by W.Froude, many experimental and theoretical studies about ship waves have been performed primarily in the fields of naval architecture and partly in coastal and harbor engineering.(1)-(3),(11),(13)-(15) The first theoretical treatment about ship waves was the application of the solution for the problem of "Waves generated by a point impulse moving with a constant speed on water surface", which gives the similar wave pattern to the actual one.(3),(13) Applying the thin ship theory and/or the slender body theory to the problems about flows around ships, the more strict solutions for the water surface undulations around ships can be obtained using the point source distributions or the Green's functions to satisfy the adequate boundary and radiation conditions under such assumptions that the beam and/or draft of ship are negligibly small compared with its length.(7),(18) More improved theories have been developed taking the effects of the curvature and thickness of ship-hull shape on the flow around the ship into account.(9),(19) Most of those studies in naval architecture, however, were conducted from the standpoint as to how the waves affected the resistances of ships. While, from the standpoint of coastal and harbor engineering, the significance of ship wave influences on the bank erosions of canals, the safety navigations and moorings of small vessels have been emphasized.(6),(10),(15),(17) In a harbor, a canal and a navigation channel the ship wave generated by a small tug boat has

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a significant influence on moored vessel rather than a large ship, because the small boat passes nearer the moored vessel with faster speed than the large ship. However, there are little quantitative data available on ship wave influences on moored vessel.

According to the results of model and field tests, the hydraulic model tests are efficient for investigating the ship waves because they yield the results similar to the prototypes.(16)

In the present paper, (1)the characteristics of ship waves generated by a large ferry boat and a small tug boat in relatively shallow water and (2)the motions of moored small cargo ship induced by the ship waves will be discussed.

MODEL TESTS

The model tests were carried out based on the Froude law of similarity at the Hydraulic Engineering Laboratory of Osaka City University, Osaka, Japan. The model scale was 1/60.

SHIP WAVES

Models of a car ferry boat and a tug boat were towed at various speeds in water of various uniform depths. A basin was approximately 40 m long and about 6 m wide.

The straight guide-rail was placed above the basin. The model ship was attached fore by short string to a carriage on the rail connected with a taut line which passed over pulleys at both ends of rail and was driven by an electric motor.(See Figs.1 and 2) The speed of ship was accurately computed from the time interval between marks made on charts during each advancing every 2 meters of ship.

The ship waves were measured by capacitance-type wave gages at five positions along a perpendicular to the sailing line as shown in Fig.3, and they were recorded on charts by using a multi-pens recorder.

The dimensions of towed ships, the ship speeds, V, and the water depths of basin, h, for the tests were listed on Table 1.

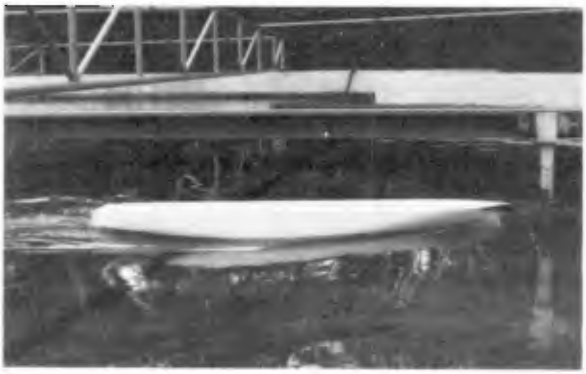
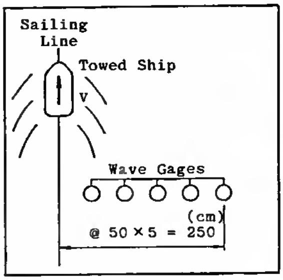
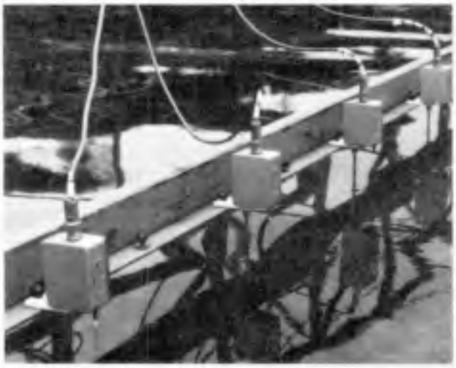


Fig.1 Model Ship Towed by Carriage

Fig.2 Electric-Motor and Pulleys



(a) Positions of Wave Gages



(b) Capacitance-Type Wave Gages

Fig.3 Wave Measurement

Table 1 Test Conditions for Ship Waves

	Ferry Boat (3624G.T.)	Tug Boat (199G.T.)
Length (cm)	136.7 (82m)	46.7 (28m)
Beam (cm)	24.3 (14.6m)	14.3 (8.6m)
Draft (cm)	9.8 (5.9m)	4.3 (2.6m)
Speed(cm/s)	55.6 - 188 (8.6knots - 29knots)	48.5 - 129 (7.5knots - 20knots)
Water Depth (cm)	14.6 - 24.6 (8.8m - 14.8m)	10.8 , 18.3 (6.5m , 11.0m)

( ) : in Prototype

MOTIONS OF MOORED VESSEL

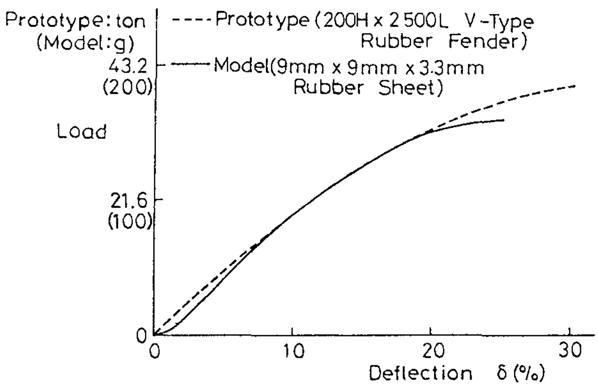
Model of small cargo ship was moored at a wharf in a usual manner with fenders and mooring lines. The model fender was made by rubber-sheet with 3.3 mm thickness, 9 mm length and 9 mm height. Its characteristic curve was similar to that of prototype as shown in Fig.4(a). Although the characteristic curve of mooring line in model, which was rubber-string with 0.9 mm square section, was different from that in prototype as seen in Fig.4(b), the slopes of tangents of those curves were almost the same each other in the test range so that the mooring line in model and prototype were considered to have the similar load-elongation relationships. Then, the rubber-string used in the tests was supposed to be suitable for the model of mooring line.

As the incident ship waves to the moored vessel were assumed the waves measured by a servo-type wave gage at a symmetrical position of the center of gravity of moored vessel, *C.G.*, in a state of rest with respect to the sailing line.(See Figs. 5 and 6)

The motions of moored vessel induced by the ship waves were measured by a ship-motion meter using potentio-meters shown in Fig.7. Angular displacements around *C.G.*(rolling, pitching and yawing) and translatory displacements of *C.G.*(surging, swaying and heaving) were obtained from the measurements of current-variations through potentio-meters installed at *C.G.* and at the upper carriage of the meter, which were linearly proportional to the vessel motions.(See Fig.8)

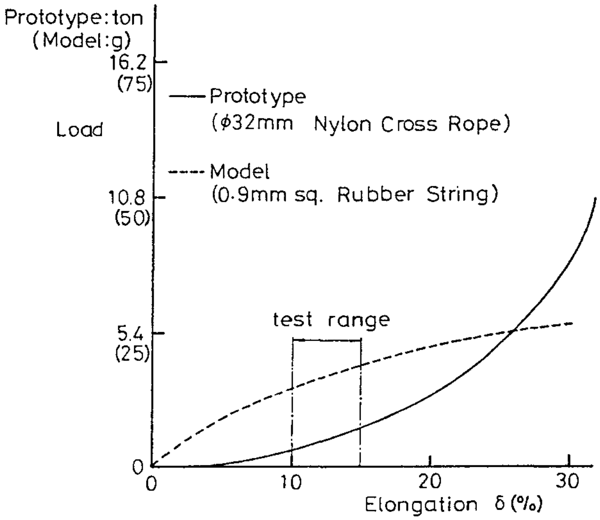
The ship waves and motions of vessel as shown in Fig.9 were recorded on magnetic-tapes by using a multi-channels data-recorder.

The dimensions of moored vessel and towed ship, the speeds of towed ship, V, the water depths at navigation channel, h, and at the wharf and natural periods of moored vessel motions were listed on Table 2.



(a) Fender

Fig.4 Characteristic Curves of Mooring Facilities



(b) Mooring Line

Fig.4 Characteristic Curves of Mooring Facilities

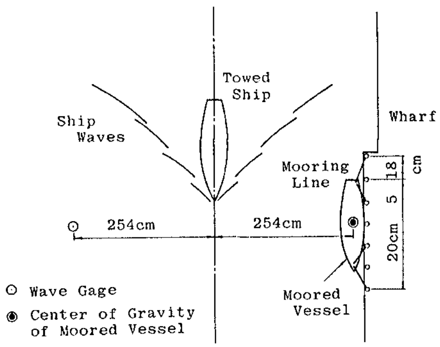


Fig.5 Model Set-Up

Fig.6 Servo-Type Wave Gage

Fig.7 Ship-Motion Meter

(a) Potentio-Meters Installed at *C.G.*

(b) Potentio-Meters Equipped on Upper Carriage

Fig.8 Measurement of Vessel Motion

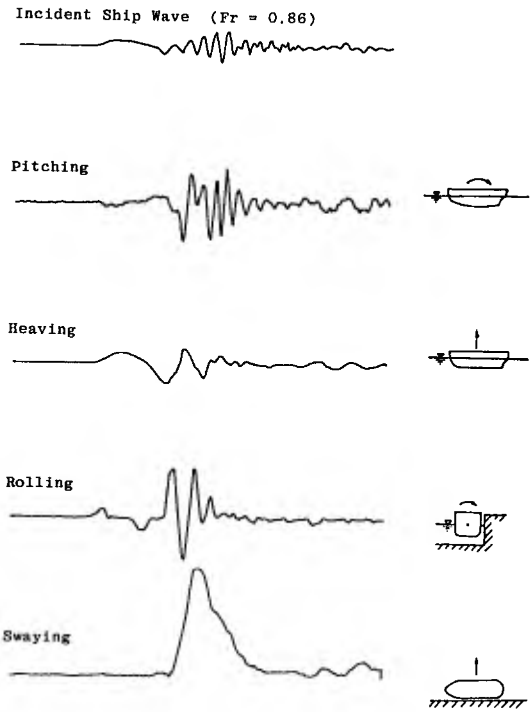


Fig.9 Time-Histories of Ship Waves and Vessel Motions

RESULTS AND DISCUSSIONS

DEFINITIONS

The maximum wave height, *Hmax*, and the maximum wave period, *Tmax*, in ship wave train were defined as Fig.10.(3) The maximum wave height is the vertical distance of the maximum crest above the following trough, and the maximum wave period is twice as long as the related time interval.

Maximum angular and translatory displacements of moored vessel were defined like the maximum wave height.

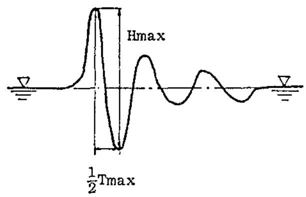


Fig.10 Definition of Maximum Ship Wave

Table 2 Test Conditions for Moored Vessel Motions

	Moored Vessel (Cargo Ship,199G.T.)		Towed Ship (Ferry Boat,3624G.T.)
Length (cm)	83.3 (50m)		136.7 (82m)
Beam (cm)	15.0 (9m)		24.3 (14.6m)
Draft (cm)	Full Condition	Light Condition	9.8 (5.9m)
	5.5 (3.3m)	2.3 (1.4m)	
Water Depth (cm)	8.2 (4.9m) at Wharf		18.3 (11m) at Navigation Channel
Speed(cm/s)	——		53 - 185 (8.2knots-29knots)
Natural Period (Moored at Wharf) (sec)			
	Full Condition	Light Condition	
Pitching	0.6 - 0.7 (4.6 - 5.4)	0.6 - 0.7 (4.6 - 5.4)	
Rolling	1.2 - 1.25 (9.3 - 9.7)	0.6 - 0.7 (4.6 - 5.4)	
Yawing	3.7 - 4.5 (28.7-34.9)	2.7 - 3.2 (20.9-24.8)	
Surging	1.75- 2.4 (13.6-18.6)	——	
Swaying	1.0 (7.7)	——	
Heaving	0.55- 0.65 (4.3 - 5.0)	0.45- 0.6 (3.5 - 4.6)	

( ) : in Prototype

MAXIMUM WAVE PERIOD

The diverging waves are predominant in the ship waves, which originate from the hump of water surface at the bow and the hollow at the stern advancing with together the ship. Then, the characteristic period $T_0 = 2\pi V/g$ (g:acceleration of gravity) was introduced to represent the inherent period of waves generated by the ship going with the speed of V. The values of $Tmax/T_0$ indicate which the ship waves with period $Tmax$ are "deep water waves" or "shallow water waves", because T_0 corresponds to the period of deep water wave with the phase velocity of V. The ratios of $Tmax$ to T_0 were obtained as shown in Fig.11. Circles and triangles in Fig.11 denote the mean values of $Tmax/T_0$ for the cases of tug boat and ferry boat at each water-depth Froude Number, $Fr = V/\sqrt{gh}$, respectively. A hatched region means the results from field tests by Sorensen.(12)

In a region of $Fr < 0.8$, the mean values are approximately 0.8 to 0.9 for the tug boat and 0.6 to 0.8 for the ferry boat, and hence the ship waves are considered as the deep water waves. While, due to the definition of T_0, when $Fr > 0.56$ the ship waves are expected as the shallow water waves. The discrepancy between the test and the theory may be due to the fact that the apparent propagation direction of ship waves is oblique to the sailing line so that the apparent propagation velocity is less than V. From Fig.11 it is clear that the model test results agree reasonably well with the field test results, and hence there are little scale effects on the test results found.

When $0.8 < Fr < 1.0$, the mean values are almost constant to be 0.9 to 1.0 for the tug boat and around 1.2 for the ferry boat. In this range the ship waves may have the characteristics of the shallow water waves.

The region of $Fr > 1.0$ is called as the super-critical region where no waves have the greater phase velocity than the ship speed, because $\sqrt{gh}$ corresponds to the maximum wave velocity which can exist in water of depth h. In this region only the diverging waves were observed and no transverse waves were seen. The mean values of $Tmax/T_0$ take the peak values at $Fr \simeq 1.0$ and decrease to become almost constant with Fr.

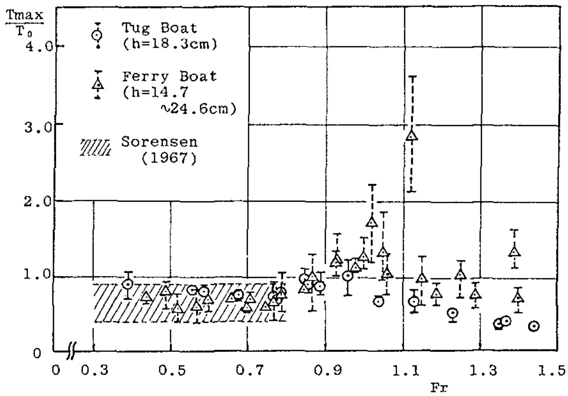


Fig.11 Ratios of $Tmax$ to T_0

From the results in Fig.11, the ratio of $Tmax$ to T_0 is supposed to relate only to Froude Number. Here, we let

$$Tmax/T_0 = C \tag{1}$$

where C is a coefficient dependent upon Fr. Then

$$Tmax = C \cdot 2\pi V/g \tag{2}$$

At a field far from a vertical cylinder in a steady free surface flow with a uniform current velocity, V, and a uniform depth, h, a wave number, k, of water surface undulation is approximately given as follows.(5)

$$\left.\begin{aligned} &\tanh kh/kh = A \cdot Fr^2 \\ &Fr = V/\sqrt{gh} < 1.0 \end{aligned}\right\} \tag{3}$$

where A is a constant equal to 3/4 or 1/2.
The period of progressive wave, T, which has the same wave number as k obtained by Eq.(3), is yielded by using the small amplitude wave theory as Eq.(4).

$$T = (\sqrt{A}/\tanh kh) \cdot 2\pi V/g \tag{4}$$

If we put

$$Tmax = T \tag{5}$$

then

$$C = \sqrt{A}/\tanh kh \tag{6}$$

The comparisons of the maximum wave periods $Tmax$ with the calculated periods T by Eqs.(3) and (4) are shown in Fig.12 for the cases of $Fr < 1.0$. The calculated values of T agree well with the values of $Tmax$. The calculated values of $\sqrt{A}/\tanh kh$ were approximately 0.9 to 1.0 for the tug boat and 0.7 for the ferry boat under the test conditions. Those values are in a good agreement with the values of $C = Tmax/T_0$ shown in Fig.11. From the comparisons of $Tmax$ with T, namely C with $\sqrt{A}/\tanh kh$, it may be concluded that (1) the wave period at the field far from the origin of waves have no reference to the draft and shape of the object producing the waves, (2) the maximum wave period can be theoretically estimated by using Eqs.(3) and (4) when the water-depth Froude Number is once determined. However, the difficulties still remain to decide precisely the value of the constant A for the specified ship-hull shape.

MAXIMUM WAVE HEIGHT

The ship wave height is closely related to wave-making resistance of ship which varies with ship-length Froude Number, $F_L = V/\sqrt{gLs}$ (Ls : ship length).(8) The maximum wave height is inversely proportional to a cubic root of a distance from the sailing line, x.(2),(4) Considering the facts above mentioned, the non-dimensional maximum wave height $(Hmax/B)(x/L)^{1/3}$ was introduced to be investigated their changes with F_L. B is a ship beam and L a wave length for the period $Tmax$ and the water depth h.

As shown in Fig.13, the non-dimensional maximum wave height for both the ferry and tug boats increase with F_L until critical value. At $F_L \simeq 0.5$ they attain the peak values. When $F_L > 0.5$, those values decrease with F_L. The changes of non-dimensional maximum wave heights with F_L seem similar to those of wave-making resistance coefficients as expected. Although the data show some scattering, it is clear that the non-dimensional maximum wave heights depend mainly upon the ship-length Froude Number but slightly upon the ratio of water depth to ship draft and the water-depth Froude Number.

MOTIONS OF MOORED VESSEL

As shown in Fig.14, the ship waves are so small that the motions of moored vessel induced by them are also small in a region of $Fr < 0.7$ to 0.8.

In a range of 0.7 to $0.8 < Fr < 1.0$, the wave height increases rapidly with Fr. The exciting force on the moored vessel might be considered proportional to $Hmax^2$. As a sequence, the rolling and swaying motions of vessel rapidly increase with Fr. The cusp line, namely the apparent crest line, of ship waves approaches perpendicular to the bow-stern line of moored vessel, hence the pitching and surging motions become large. The ship waves with large height and long length go into the gap between the moored vessel and the wharf, and the phase lag between the exciting forces on the bow and the stern of the vessel cause the large yawing motion of vessel.

In the super-critical region of $Fr > 1.0$, the motions of moored vessel increase with Fr as well as the maximum wave period, although the maximum wave height decrease to become almost constant.

Thus, the motions of moored vessel seem to depend upon the wave heights, wave length and wave direction. The heaving motion, however, may be considered dependent upon the vertical motion of the water surface (wave height). The maximum heaving motion seems to have almost the same amplitude as the maximum wave in a range of $0.6 < Fr < 1.4$ without regard to the wave conditions and the mooring conditions as presented in Fig.15.

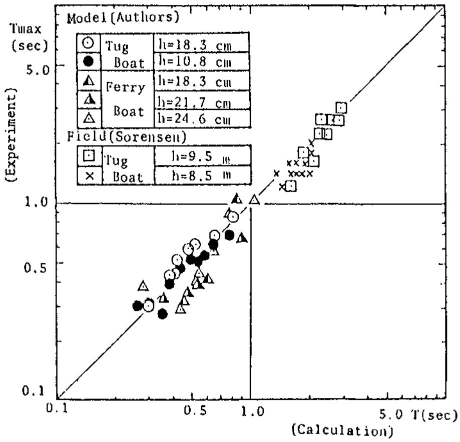


Fig.12 Comparisons of *Tmax* with *T*

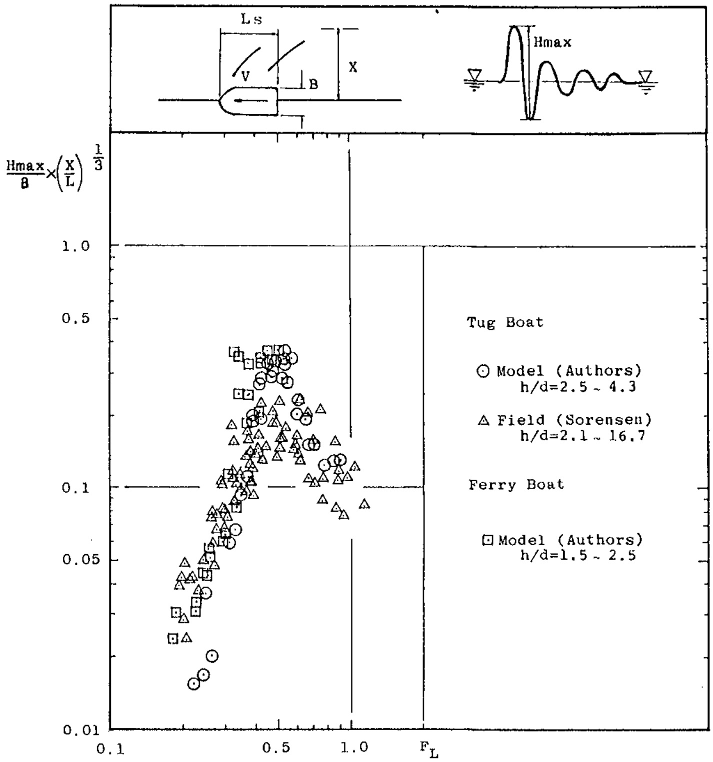


Fig.13 Non-Dimensional Maximum Wave Heights

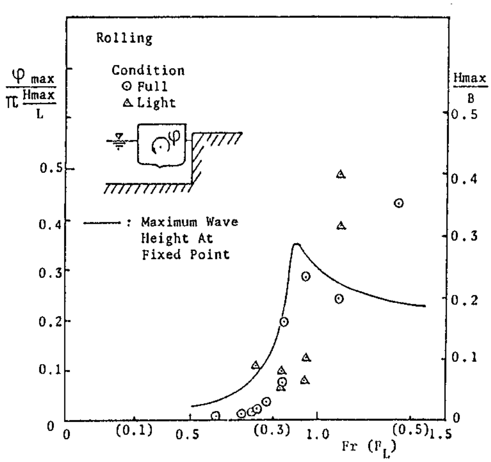


Fig.14 Maximum Rolling Motions of Moored Vessel

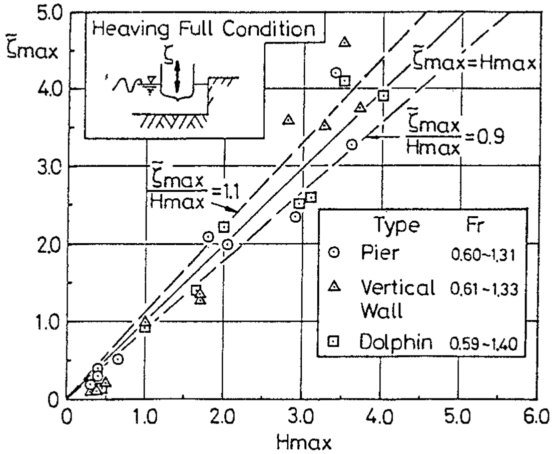


Fig.15 Maximum Heaving Motion of Moored Vessel

FOURIER TRANSFORMS

For analyzing the transient phenomena such as the ship waves and the moored vessel motions induced by them shown in Fig.9, the Fourier transform is generally used.

According to the results by the Fourier transforms of the incident ship waves and the motions of moored vessel, the motion of vessel resonate to have a large amplitude at the natural period in each mode as shown in Fig.16. At the period when the maximum amplitude of ship wave component occurs, the amplitude of motion of vessel is also large. From the results by the Fourier transforms, the response factors of moored vessel to the waves might be obtained. The moored vessel motion to the arbitrary incident waves may be predicted by using those factors.

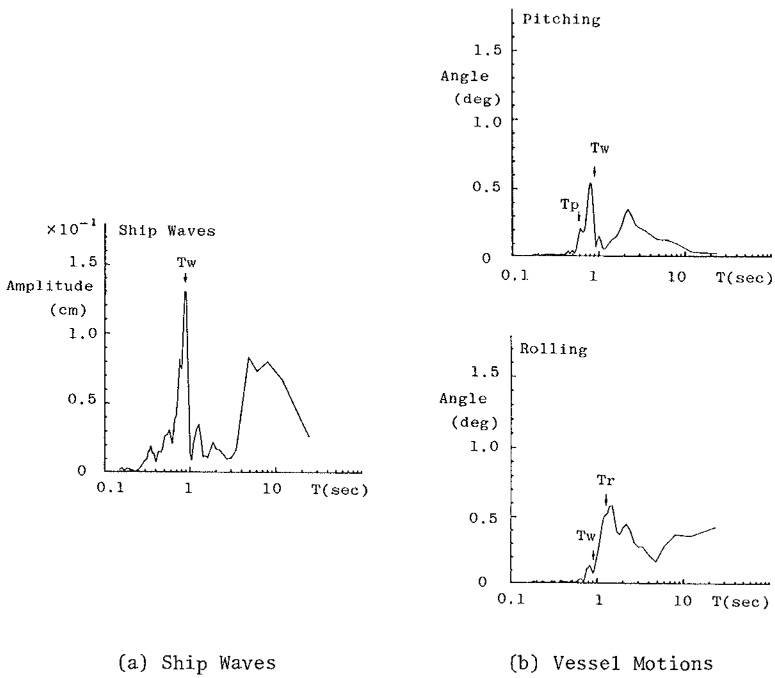


Fig.16 Fourier Amplitudes of Ship Waves and Vessel Motions

CONCLUSIONS

The maximum height and the maximum period of ship wave and the motions of moored vessel induced by the ship waves were investigated in a wide range of the water-depth and ship-length Froude Numbers.

The maximum wave period is related to the water-depth Froude Number and can be estimated theoretically when its value is once specified.

The non-dimensional maximum wave height depends upon the ship-length Froude Number. The wave length refers to the wave period, which is decided by the water-depth Froude Number. Then, the maximum wave height is considered as a function of the ship-length and water-depth Froude Numbers.

The relationships between the maximum angular and translatory displacements of moored vessel and the maximum ship waves were obtained. The maximum displacements of vessel are related to wave height, wave period and wave direction.

The responses of moored vessel to the ship waves were investigated by using the Fourier transforms. The vessel motion responses are large at the natural period and at the period when the maximum amplitude of component wave occurs.

The influences of the passing ships, with the speeds of 10 knots or less (usually $Fr < 0.5 \sim 0.6$) through fareways or navigation channels, are considered not to be significant on the small cargo ships moored at the wharves.

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REFERENCES

(1) Brebner,A.,P.C.Helwig and J.Carruthers : Waves Produced by Ocean-Going Vessels, A Laboratory and Field Study, Proc. of 10th Conf. on Coastal Eng., pp.455-465, 1966

(2) Havelock,T.H. : The Propagation of Groups of Waves in Dispersive Media, with Application to Waves on Water Produced by a Travelling Disturbance, Proc. Roy. Soc., Ser.A 81, pp.398-430, 1908

(3) Johnson,J.W. : Ship Waves in Navigation Channels, Proc. of 6th Conf. on Coastal Eng., pp.666-690, 1958

(4) Kurata,K., K.Oda and S.Hirai : Ship Waves in Shallow Water and Their Effects on Moored Vessel, Proc. of 30th Japanese Conf. on Coastal Eng., pp.598-602, Nov. 1983 (in Japanese)

(5) Kurata,K. : Free Surface Flow around Vertical Cylindrical Object, 1984 (unpublished)

(6) Lee,T.T. : Ship Generated Waves in Navy Marina at Pearl Harbor, Tech. Rep. No.38, James K.K. Look Laboratory of Oceanographic Eng., Univ. of Hawaii, Apr. 1976

(7) Mei,C.C. : Flow around a Thin Body Moving in Shallow Water, Jour. of Fluid Mech., Vol.77, Part 4, pp.737-751, 1976

(8) Newmann,J.N. : Marine Hydrodynamics, 1980

(9) Okamura,H., T.Inui and H.Kajitani : Analysis of Ship Waves Propagating on a Non-Uniform Flow, Jour. of the Soc. of Naval Architects of Japan, Vol.138, pp.37-45, Dec. 1975 (in Japanese)

(10) Powell,A. and W.R.McCreight : Effect of Ship Waves on Vessels and Ocean Structures, US-JAPAN Conf. on Development and Utilization of Natural Resources, Tokyo, 1982

(11) Saunders,H.E. : Hydrodynamics in Ship Design, Vol.1, Chap.10, p.168-p.184, The Soc.of Naval Architects and Marine Engineers, New York, 1957

(12) Sorensen,R.M. : Investigation of Ship-Generated Waves, Jour. of the Waterways and Harbors Div., Vol.93, WW1, pp.85-99, ASCE, 1967

(13) Sorensen,R.M. : Ship-Generated Waves, Advances in Hydroscience, Vol.9, p.49-p.83, Academic Press, New York, 1973

(14) Stoker,J.J. : Water Waves, p.219-p.243, Interscience Publishers, New York, 1957

(15) Takenouchi,Y. and K.Nanasawa : About "Gunkan-Nami"(Warship Wave) which Reaches on the Imabari Beach as Significant Breakers, The Jour. of the Oceanographical Soc. of Japan, Vol.17, No.2, pp.20-30, June 1961 (in Japanese)

(16) Tanaka,H. et al. : Some Application of the Wave Analysis on the Geomi-Models and Their Actual Ship, Jour. of the Soc. of Naval Architects of Japan, Vol.126, pp.11-24, Dec. 1969 (in Japanese)

(17) Tanaka,H. and H.Adachi : Influence of Waves due to Large Ship upon Small Ships and Ocean Structures, US-JAPAN Conf. on Development and Utilization of Natural Resources, Tokyo, 1982

(18) Tuck,E.O. : Shallow-Water Flows Past Slender Bodies, Jour. of Fluid Mech., Vol.26, Part 1, pp.81-95, 1966

(19) Ursell,F. : On Kelvin's Ship-Wave Pattern, Jour. of Fluid Mech., Vol.8, Part 3, pp.418-431, 1960