Journal of Navigation and Port Research International Edition
Vol.33, No.2 pp. 105~110, 2009 (ISSN-1598-5725)

A Study on Shape and Height of Shipwaves

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Abstract : *Shipwaves can have harmful effects on ships working on the sea, in a harbour or navigational channel and caused beach erosion, seawall destruction. This study aims to investigate describe the characteristics of the wave pattern generated by an individual model ship tested at different velocities and hull forms for a given water depth and to investigate the variations at a given distance from the sailing line under the same conditions. As a result, the angles* α*'s by model ship tests are smaller than those by real ship ones. Wave heights decreases with an increasing the mid-ship cross sectional area* A_s*. The maximum wave height and period increase rapidly in the subcritical speed, and beyond the critical speed the height and period decrease with increasing depth Froude number. And the period keeps constant with the distance from the sailing line.*

Key words : *Shipwaves; Diverging wave; Transverse wave; Maximum wave height; Maximum wave period; Shallow water; Depth Froude number*

1. Introduction

Shipwaves generated by a moving ship have chiefly harmful effects on small boats working on the sea, on other ships in a harbour or navigation channel, and on shorelines or channel banks. Recently these destructive actions which shipwaves caused have been reported the judgement of Korea Maritime Safety Tribunal, and countermeasure works to decrease shipwaves or their damages have been discussed.

Shipwaves are made up of two kinds of waves, namely one is diverging or oblique waves that form at the bow and move out from the ship, and the other is a series of transverse waves that also form at the bow and move forward with their crests normal to the ship sailing line. This pattern is steady with respect to a ship moving at a constant velocity.

Some investigations of the waves generated by a moving ship have been conducted to evaluate the configuration of the wave pattern and the characteristics of the individual wave phases from both the analytical and the experimental points of view. Many analytical, numerical or experimental studies(Shin and Jung, 2003; Gang et al, 2007; Kang et al, 2008) on the characteristics of shipwaves have been executed since Froude(1877), Froude(1889), Havelock(1908) and Lamb(1932), and useful knowledges have been accumulated. It seems that there have been little discussion and investigations on the characteristics of individual shipwaves occurred by different hull forms of ships with the appearance of various different types of ship.

This study aims to describe the characteristics of the wave pattern generated by an individual model ship tested at different velocities and hull forms for a given water depth, i. e., at different deep, transitional and shallow water Froude numbers and in addition, to investigate the variations at a given distance from the sailing line under the same conditions.

2. Model Experiments

Taking the characteristics of the ship waves generated by a moving ship into consideration, the maximum non-dimensional wave height H_{max}/d is mainly governed by the following parameters.

$$\frac{H_{max}}{d} = \Phi\left(\frac{V_s}{\sqrt{gh}}, \frac{L_s}{h}, \frac{d}{h}, \frac{S}{L_s}, \frac{gT_{max}^2}{h}\right) \tag{1}$$

where, H_{max} is the maximum wave height at a point in question, d the ship draft, v_s the ship's speed, g the gravitational acceleration, h the water depth, L_s the ship's length, S the perpendicular distance from the sailing line to the point of wave measurement and T_{max} the period of the ship's wave for which the H_{max} is presented. In addition, $v_s/\sqrt{gh}$ means the depth Froude number(F_h), and unless otherwise stated, the Froude number will use the still water depth as the length parameter.

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In the present study, the effects of the following parameters on the characteristics of the shipwaves are mainly discussed. Also, the ratio of speed to length $v_s/\sqrt{L_s}$, called the relative speed, will be used for the case of an undefined depth instead of the depth Froude number F_h.

$$\frac{H_{max}}{d} = f(\frac{v_s}{\sqrt{gh}}, \frac{S}{L_s}) \quad (2)$$

A series of model experiments were carried out in the model basin(28m in length, 6m in width and 1m in depth) of the Navigational Operating Laboratory at Korea Maritime University. All tests were made with fresh water in the model basin. The wave absorbing filters were installed at the both sides of the basin wall to diminish wave reflection from side walls as small as possible. Fig. 1 shows the sketch of shipwave experiment.

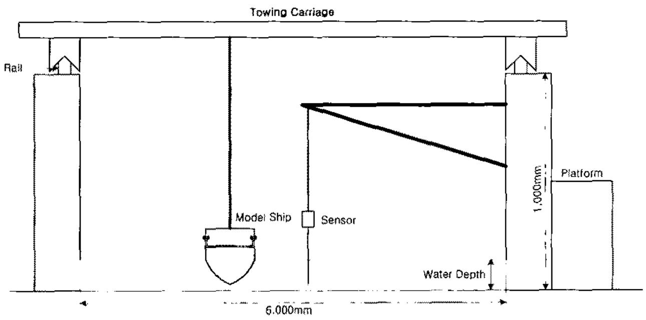


Fig. 1 Sketch of shipwave experiment

In these experiments ship models were towed at various speeds in water of a constant depth within a range of $0.6 \leq F_h \leq 1.4$, and the wave profiles were measured with capacitance-type wave gauges at various distances along a perpendicular to the sailing line after the model ship had attained a constant speed.

The type and size of the model ships used in experiments are demonstrated in Table 1.

Table 1 Type and size of model ships used in experiments(unit : cm)

Type of model ship	L_s	Breadth	d
Patrol boat	64.0	15.6	1.8
Fishing boat	43.0	8.7	3.6
Bulk carrier	76.5	12.0	5.0
Container ship	72.0	8.2	3.9

A typical example of a wave height record is shown in Fig. 2. The maximum wave height usually represents the vertical distance where a distance from a crest(trough) to a trough(crest) is largest. The duration for the case of the maximum wave height is defined as the maximum half period($T_{max}/2$) of the wave. The maximum period(T_{max}) or period means a twice period of the maximum half period.

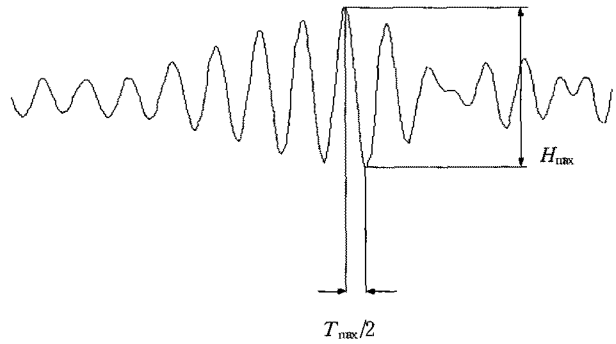


Fig. 2 Maximum wave height H_{max} and maximum half period $T_{max}/2$

3. Pattern of ship waves

In deep water, coordinates of the wave crests in the Kelvin wave pattern are demonstrated as follows(Lamb, 1932).

$$x=(n\pi\, v^2_s/2g)(5\cos\alpha' - \cos 3\alpha') \quad (3)$$

$$y=(-n\pi\, v^2_s/2g)(\sin\alpha' + \sin 3\alpha') \quad (4)$$

where, x is the coordinate measured in the direction of the sailing line from the disturbance, y at the right angle to x and normal to the sailing line, and n=0, 1, 2, 3, etc.. Also α' is the angle formed by the sailing line and a line between the disturbance and the point in question.

The wave components between $|\alpha'|$=0°and 35°16′ form the transverse wave system and those between 35°16′ and 90° do the diverging wave system.

The wave crest pattern presented in Fig. 3 represents the characteristics of the wave crests generated by a ship moving at a constant velocity in deep water. The pattern includes pairs of oblique or diverging waves that form at the bow and move out from the ship and of transverse waves that also form at the bow and move forward with their crests normal to the ship sailing line. The Kelvin wave pattern is in general agreement with the pattern of model towing tank experiments.

The cusp locus angle α between the sailing line and cusp locus lines, which is expressed by dotted lines becomes 19°28′ which is independent of the speed of the ship provided deep-water conditions exist.

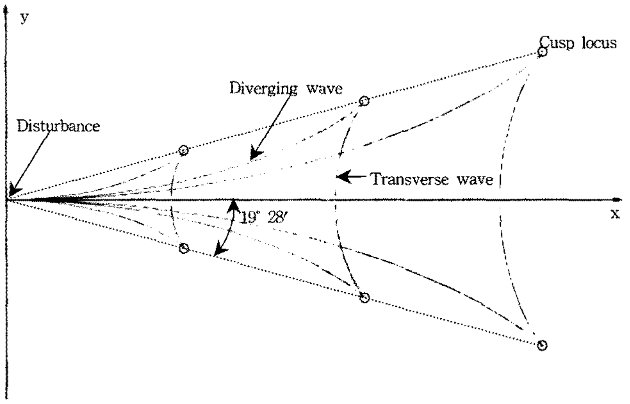


Fig. 3 Wave crest pattern in deep water

Hovgaard's observations(Johnson, 1958) showed that the cusp locus angles α's almost agreed with those of the Kelvin wave pattern except those by model tests as demonstrated in Fig. 4. In the Fig. ● represents the results by actual ships and ▲ does the results by model ships used in the test. It seems that the angles α's by model ship tests are smaller than those by real ship ones and that the angles decrease with thinner bow entrance angles and higher deep water speeds.

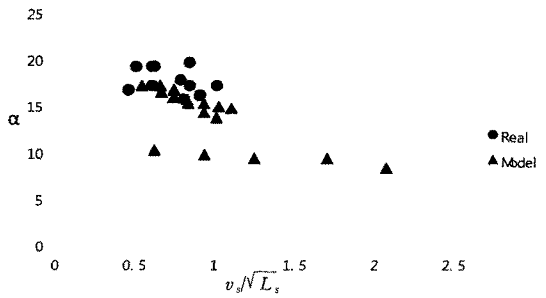


Fig. 4 Cusp locus angles measured by Hovgaard

In addition, the angle α between the sailing line and the diverging wave is defined as follows(Havelock, 1908). In deep water in case $h \to \infty$, the angle α becomes 19°28′.

$$\alpha = \cos^{-1}\frac{\sqrt{8[1-(2kh/\sinh 2kh)]}}{3-(2kh/\sinh 2kh)} \quad F_h \leq 1.0 \qquad (5)$$

$$\alpha = \sin^{-1}\frac{\sqrt{gh}}{v_s} \quad F_h > 1 \qquad (6)$$

Fig. 5 shows cusp locus angle as a function of depth Froude number. As the speed increases or the water depth decreases, the angle increases, even up to 90 degrees at the critical speed(F_h=1). Beyond the critical speed the angle decreases gradually down to 19°28′. This general tendency is in good agreement with the results of model experiments(Johnson. 1958).

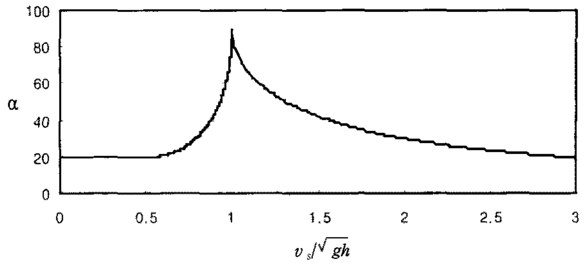


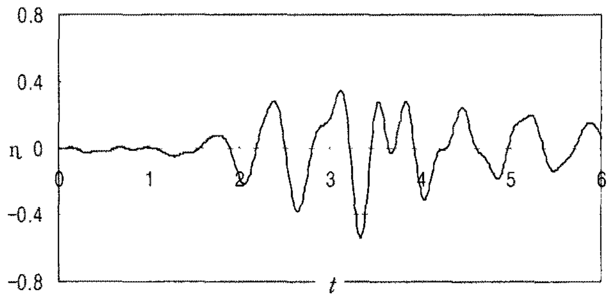
Fig. 5 Cusp locus angle as a function of depth Froude number

4. Wave heights

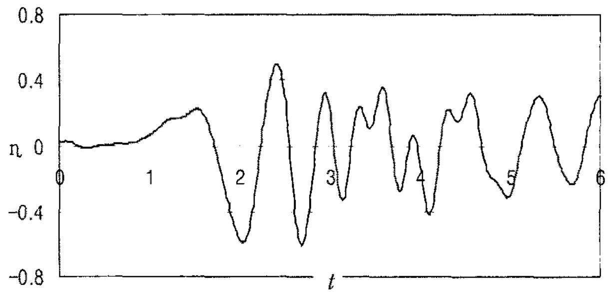
The diverging and transverse waves are highest at the bow and become successively lower as the crests reoccur in the aft direction. The wave-crest lengths increase in the aft direction so that the energy per unit crest length and thus the wave height must decrease.

Fig. 6's shows the water surface time history at two locations along a line normal to the sailing line for a model patrol ship traveling in water of constant depth at depth Froude numbers of 0.8 and 1.0.

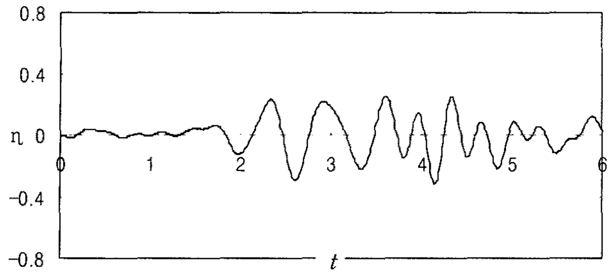
The maximum wave height increases and decreases respectively with increasing Froude number and distance in the scope of $F_h \leq 1.0$.



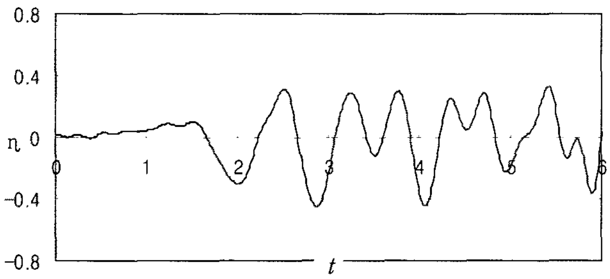
(a) Time variations of patrol boat(F_h=0.8, S=1.0L_s)



(b) Time variations of patrol boat(F_h=1.0, S=1.0L_s)



(c) Time variations of patrol boat(F_h=0.8, S=2.0L_s)



(d) Time variations of patrol boat(F_h=1.0, S=2.0L_s)

Fig. 6 Time variations of shipwaves

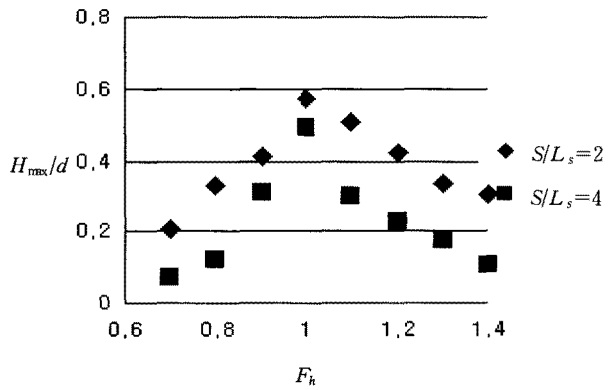


Fig. 7 Maximum wave heights with F_h(patrol boat)

In Fig. 7, the maximum non-dimensional wave heights with S/L_s as a parameter are presented. In the Fig., the symbols ◆ and ■, respectively indicate the wave heights at distances twice and four times ship's length from the sailing line.

At increasing depth Froude numbers below one, the maximum wave height increases rapidly to a maximum at a ship speed near the critical speed. Beyond the critical speed the height at any location in the wave system decreases with increasing depth Froude number.

The wave height is getting smaller with distance. From wave energy conservation, the transverse wave decreases in height at a rate inversely proportional to the square root of the radially advanced distance from the point of wave generation. On the other hand, the cusp height does at a rate inversely proportional to the cube root of the distance for a given velocity(Havelock, 1908). It is known that the heights of waves generated are more dependent on a ship's velocity and the water depth than on its displacement or hull geometry.

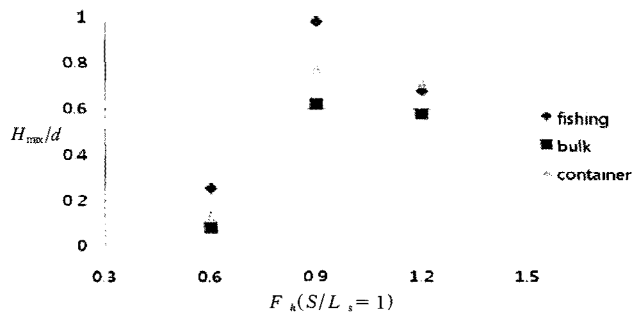


Fig. 8 Maximum non-dimensional wave height for different ship types(S/L_s=1.0)

Fig. 8 denotes the maximum non-dimensional wave height with F_h as a parameter. As mentioned previously, below one of F_h the maximum wave height increases and then beyond the critical speed the height decreases with increasing depth Froude number for each ship.

The mid-ship cross sectional area A_s(breadth×draft) of fishing boat, container ship and bulk carrier, respectively, is 31.3cm^2, 32.0cm^2 and 60.0cm^2. The wave height H_{max}/d decreases with an increasing A_s without regard to ship's type. It means that H_{max}/d is seen to be well evaluated with the mid-ship cross sectional area A_s of the ship as in Fig. 8.

This is in good agreement with Johnson's result(1968) obtained from model test.

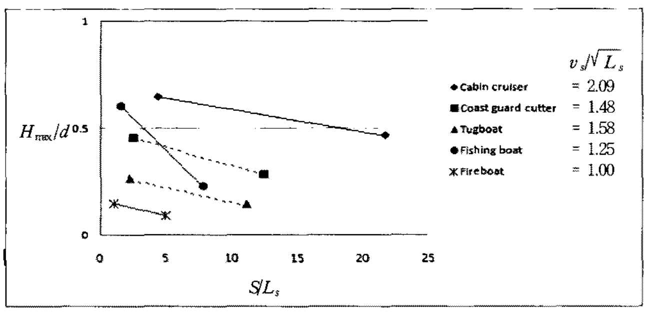


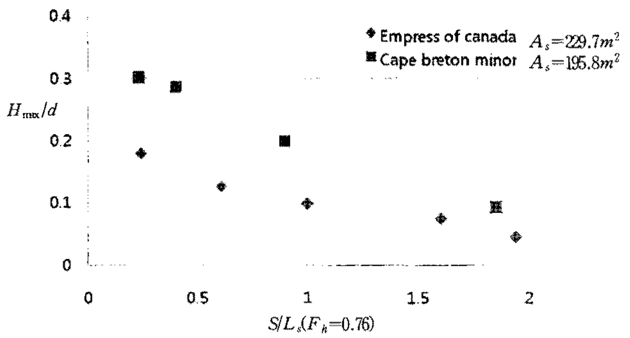
Fig. 9 Maximum wave heights with distance from the sailing line

Fig. 9 shows the maximum non-dimensional wave heights measured with actual ships(Sorensen, 1967).

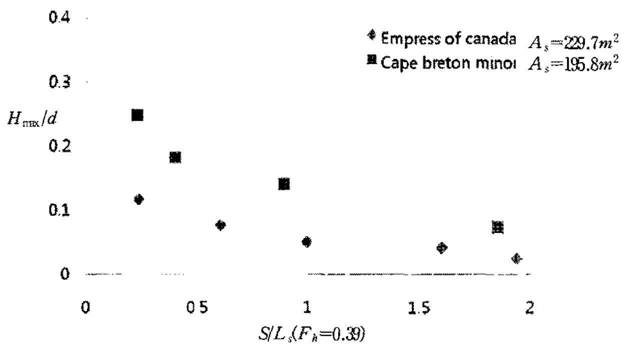
In these cases, the mid-ship cross sectional area A_s of cabin cruiser, coast guard cutter, tugboat, fishing boat and fireboat, respectively, is 1.26m^2, 3.35m^2, 5.7m^2, 3.46m^2 and

26.46m^2. As demonstrated in Fig. 8, the wave height H_{max}/d decreases with an increasing A_s. It is verified that the relationship between H_{max}/d and A_s can be applied for actual ships.

Other examples by real ships expressed well the relationship between H_{max}/d and A_s are shown in Fig. 10's(Brebner, 1966).



(a) Maximum wave heights with distance(F_h=0.76)



(b) Maximum wave heights with distance(F_h=0.39)

Fig. 10 Maximum wave heights with distance

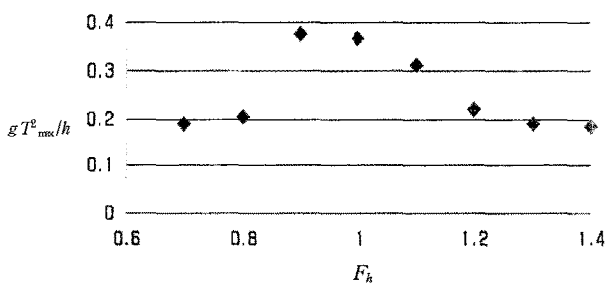


Fig. 11 Wave periods with F_h(patrol boat, S/L_s=2)

Fig. 11 denotes the wave period related to H_{max} with the depth Froude number F_h.

As seen from Fig. 11, the period generally increases to a maximum at a ship speed near the critical speed and then decreases at a continually reduced rate. The period is independent of both the ship size, shape and the distance S from the sailing line(Sorensen, 1967).

5. Conclusion

The characteristics of the wave pattern generated by an individual ship have been discussed. Main conclusions obtained in the present study are summarized as follows.

The angles α's by model ship tests are smaller than those by real ship ones

The wave height H_{max}/d decreases with an increasing A_s without regard to ship's type. Maximum non-dimensional wave height H_{max}/d is seen to be well evaluated with the mid-ship cross sectional area A_s.

The maximum wave height and period increase rapidly in the subcritical speed, and beyond the critical speed the height and period decrease with increasing depth Froude number. And the period keeps constant with the distance from the sailing line.

Acknowledgement

The last author would like to express his gratitude for the financial assistance provided by the Korea Sanhak Foundation.

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Received 27 November 2008
Revised 30 March 2009
Accepted 30 March 2009