Study on Characteristics of Stern Waves Including Viscous Effect

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Abstract

Characteristics of stern waves are investigated using some simple mathematical hull forms. Drastic changes of stern wave generation due to the incoming bow wave condition are observed by flow visualization. Some of the numerical analysis is tried how the "waves" and "viscous" mutually interacts. Results are compared with experiments. Different features of wave resistance from pure potential flow case, Froude number dependency of boundary layer growth and instability of stern wave generation on some speed to speed are discussed. Present paper is reporting together with authors' previous experimental works(1).

1. Investigation of characteristics of stern waves

We observed stern wave patterns of several simple hull forms first to look into their comprehensive characteristics.

Following remarkable characteristics were found. Not only the starting point of stern waves but the phase of stern waves varies with Froude number(Fn). As shown in Fig.1 the wave pattern is different from that of linear Kelvin waves, and the surface of stern waves fluctuates remarkably. The strength of stern wave fluctuation also varies with Froude number. The free surface fluctuates remarkably and the stern waves become strong in a velocity range where the resistance curve becomes hump(Fn=0.30) whereas the free surface fluctuation and the stern waves themselves become weak near at the hollow point of resistance curve(Fn=0.27).

Fig.1 Wave pattern pictures left; Fn=0.27 right; Fn=0.30

Through the experiments of beam-length series models and draft series models, it was found that the changes of flow phenomena are great in case of the deep drafted thin ship model. So that a more detailed investigation was carried out using the deep drafted and wall-sided thin ship model of which length-breadth ratio and breadth-draft ratio are 11.17 and 0.358, respectively.

The measurement of wave profiles and pressure distributions on the hull surface and wave heights around the stern were carried out and following results have been obtained. The starting point of stern waves, which is generally a little fore from AP, moves to the stern as the trough of bow wave approaches the stern end. This is related to the wave slope near the stern. The free surface fluctuation of stern waves becomes remarkable as the wave slope at the stern becomes large.

The wave slope near the stern end affects a pressure gradient around the stern flow field and eventually a development of boundary layer and separation. Flow observations and velocity measurements near the free surface around stern were carried out and following results have been obtained. The velocity in the boundary layer near the free surface is affected by the bow wave orbital motion. The boundary layer development is accelerated at where the wave slope is increasing and decelerated at where the wave slope is decreasing. Although the development of boundary layer is remarkable as the crest of bow wave approaches the stern end, the separation is not observed. So that, the separation of boundary layer does not contribute to the generation of the stern waves.

2. Computation of interaction between ship waves and boundary layer-wake

To investigate how far the interaction with waves and hull extends the generation of stern waves and also the interaction between ship waves and boundary layer-wake, following method was employed to comprehend the flow field.

Guilloton's method, which is a higher order theory of the thin ship theory and includes the diffraction effect and partially non-linearity of hull and free surface conditions, was used in the calculation of the external wavy potential flow. The computational procedure used here is not Guilloton's original scheme, but a modified method originated by Gadd(2). According to the Guilloton's method given by Gadd, vertical transformation is based on the linearized free surface condition, so transformation does not correspond to stream lines but isobar approximately. So that the flow calculated by this method does not correspond to the real flow accurately on the hull surface at deep location. For this reason, we use the vertical velocity component for transformation in order that the transformed lines may correspond to stream ones. This is according to the concept of Lagrangean coordinate.

The calculation of boundary layer-wake was carried out applying integral method under small cross-flow assumption. As to the boundary layer calculation, the entrainment equation was employed as an auxiliary equation. Thompsom's chart was used to determine the entrainment rate. Mager's model was assumed to describe the velocity components in the boundary layer with Ludwieg-Tillmann's experimental equation for local wall shear stress. As to the wake calculation, we need also the entrainment equation. The entrainment rate derived from Thompson's chart is not so precise that we employ Kang's experimental equation for wake calculation just as Larsson(4) applied. For the velocity component for wake calculation, Coles' wake law was used. The shear stress at the symmetric point in the wake was assumed to be zero. We assumed further that the boundary layer separation occurs when the shape factor for velocity profile becomes greater than 1.8. The computation was continued exceeding the assumed separation point with zero shear stress.

For the calculation of ship waves, we take account the effect of the displacement thickness of boundary layer and wake as the viscous effect on the external potential flow.

Calculating procedure is as follows. First, the external flow field and stream lines are calculated by Guilloton's method in the absence of boundary layer-wake. Second, the calculation of boundary layer-wake is carried out along the stream lines. Third, calculation of Guilloton's method is repeated on a new ship form where the displacement thickness is added. Such procedure is iterated until the calculated wave resistance converges. At the first stage of the iterative procedure, calculation shows a so called "over shoot" due to the over estimate of the displacement thickness around the stern end. So that the displacement thickness is artificially attenuated at very beginning few iterations. Except for the calculation of wake and the iterative procedure, the method used in the present work is similar to that given by Hinatsu, et al.(4) basically.

Following results were obtained by Guilloton's method. The diffraction effect is shown around the bow and stern. Although the source strength around the bow does not vary much changes with Froude number, e.g. the strength around the stern becomes strong at Fn=0.30, weak at Fn=0.27. This tendency corresponds well to the experimental observation.

Through this calculation, it was found that the boundary layer and wake, especially around the afterbody, are affected by the bow waves. The displacement thickness becomes large at the wave crest on the hull and small at the trough as shown in Fig.2. At the velocity range beginning from hollow to hump shown in wave resistance curve (Fig.4), the displacement thickness expands great so that source strength around stern is attenuated. On the other hand, the attenuation is little at the way from hump to hollow. This result means that the effective ship length, which is equivalent to the wave system, becomes short at range from hollow to hump of the resistance curve, and this is corresponds to the experimental wave analysis.

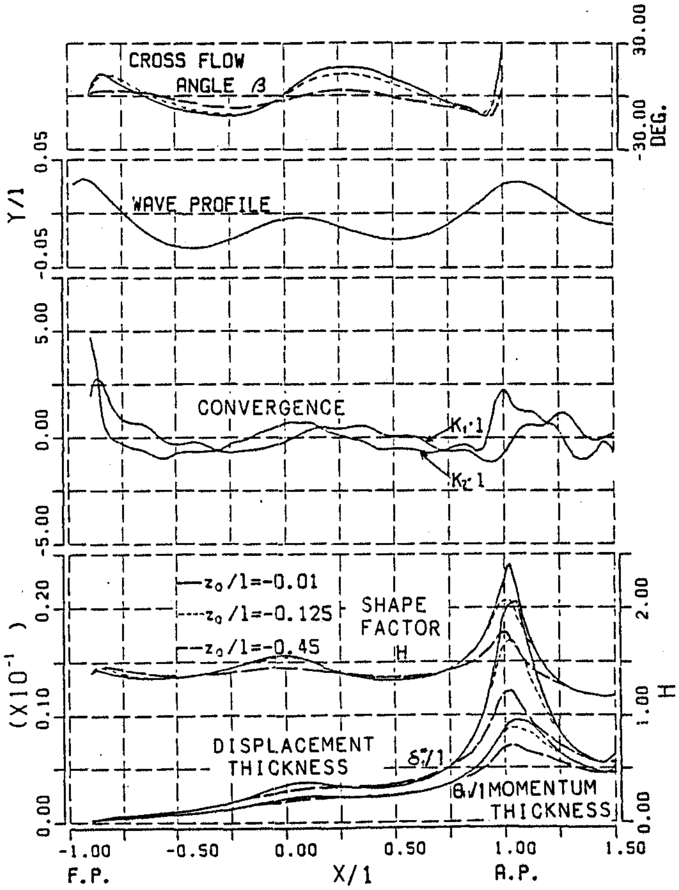

Fig.2 Calculated boundary layer parameter Fn=0.27 Rn=2.01×10^6

In case of the double model flow, the displacement thickness decreases gradually in the wake after passing through the stern position. But when ships run with finite Froude number, it increases depending on the wave orbital motion (Fig.3). The increment of displacement thickness in the near wake is remarkable at the way from hollow to hump of wave resistance, which invites large attenuation of the wave resistance comparing to that in ideal fluid. Fig.4 shows the wave resistance curves. In this figure "OPEN WAKE" is a result obtained by ignoring the increase of the displacement thickness in wake.

It is experienced that generation of stern waves is unstable at the speed from hollow to hump. Present calculation also experiences a similar unstable behavior and it takes more iterations to get the solution at this speed range. This unstableness is caused by the increment of displacement thickness in the near wake.

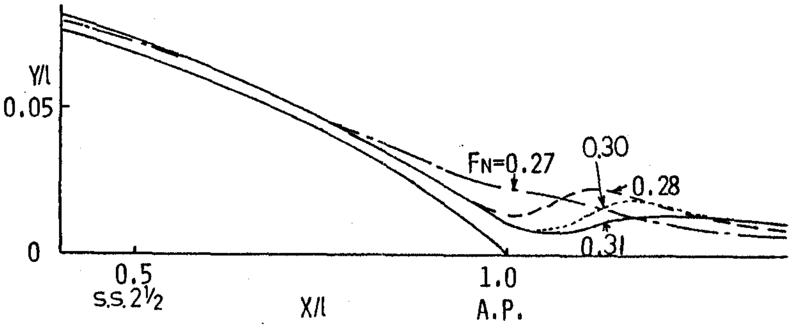

Fig.3 Displacement thickness (z/l=-0.01)

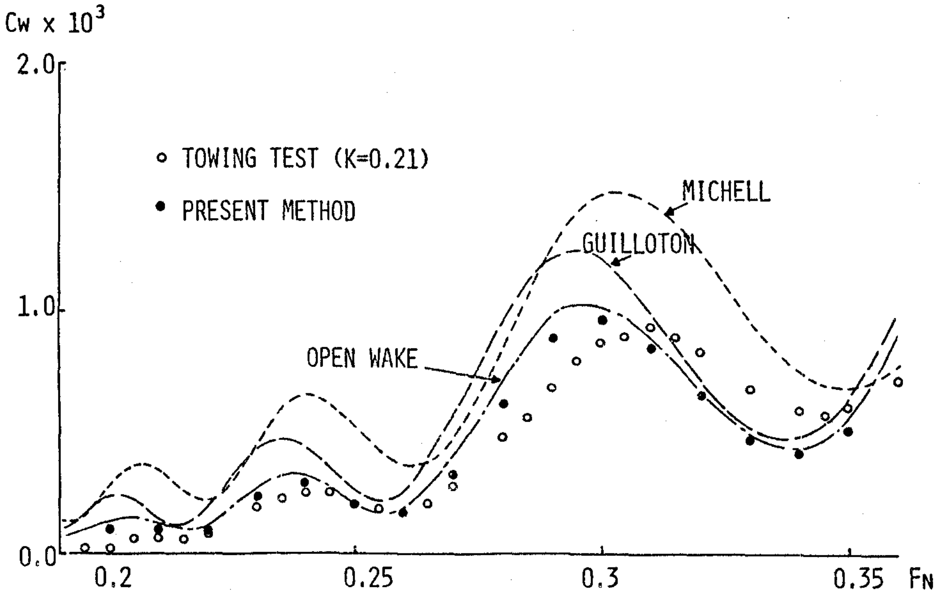

Fig.4 Wave resistance curves

References

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2) Gadd, G.E.: Wave Resistance Calculation by Guilloton's Method, T.R.I.N.A, Vol.115 (1973)

3) Larsson, L., Chang, M.S.: Numerical Viscous and Wave Resistance Calculation Including Interaction, 13th Symposium on Naval Hydrodynamics, Japan (1980)

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Discussion

Tuck: How are stern waves are defined?

Doi: It is very difficult. In the present study, stern waves are defined as the waves which obviously diverge from the stern.

Newman: The radically different behavior of the wake for closely spaced Froude numbers is remarkable. What happens downstream.

Doi: A wake survey downstream was not carried out. Probably the wake downstream is strongly affected by changes in the wake near the stern.

Schwartz: Is stern turbulence primarily a source wave of drag? What is the best way of thinking about it?

Doi: Free surface turbulence of stern waves is primarily a wave drag. I think that the free surface turbulence is not due to the turbulent boundary layer, but to the stern wave itself.

Newman: Is the wake region very shallow, or more two-dimensional?

Doi: There are two wake regions. One is the wake following the boundary layer developing on the hull surface. This wake region does extend to some depth. The other is a wake due to the free-surface turbulence. This wake region is very shallow.

Ursell: A wake region gets deep when it is thin, farther downstream, as in some stratified flows.

Doi: I agree with you. A wake region gets deep and the velocity in the wake gets large when it is thin. By the way, the black zone in Fig. 1 (wave pattern pictures) is not the wake region.

Ursell: It seems strange that the apparent wake contracts. From conservation and diffusion of vorticity one might expect the width of the wake to remain constant or to spread.

Beck: Did the tufts show no separation at all Froude numbers?

Doi: A reversing flow appears at Fn = 0.3.
This flow is not a boundary layer separation due to the bow-wave effect, but a flow due to the turbulent stern waves.

Yeung: Regarding Fig. 4, what boundary layer thickness is used for the open-wake method?

Doi: In the case of the open-wake method, the displacement thickness is used instead of the boundary-layer thickness. The displacement thickness is assumed to be constant behind the point where the displacement thickness calculated by the present method increases.