Revisiting the unsteady wave pattern of a ship

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1 Introduction

Wave pattern generated on the calm water surface by a ship cruising at constant speed has long attracted people's attention and known as the Kelvin wave pattern; its pictures are often found in text books of hydrodynamics. Careful observation of this wave pattern was claimed by Inui to serve scientific purpose to enhance ship hull forms in terms of wave making resistance. We may expect therefore that observation of unsteady wave pattern, which is generated by a ship running in incident waves, will provide scientific information of hydrodynamics of ship-wave interaction of a ship at non-zero cruising speed, even though the unsteady wave pattern is much more complicated in its structure and more difficult to measure than the Kelvin pattern.

Scientific observation of a full pattern of the unsteady wave had not been realized till recently (Ohkusu 1996). Though the technique was proposed in the eighties, nobody attempted to implement it before 1996. One reason is that tedious tank test was envisaged to do this. Neither radiation wave pattern nor diffraction wave pattern of a ship cruising at non-zero forward speed is visible because they are mixed with the Kelvin wave and the incident waves. As a consequence a special computerised technique is required to realize the observation of them. We are pleased however to find that some authors are interested in this technique and have attempted to measure the unsteady wave pattern of a ship (e.g. Lugni et al., 2003).

Modern computational methods recently developed are claimed to predict more precisely nonlinear wave-body interaction. We are well aware, however, that mere comparison of ship motions computed and measured is not appropriate to claim the advantage of such advanced computational methods because even some heuristic method like the Strip theory often does fairly well if we are concerned only with the ship motions. We understand that comparison in the wave pattern and/or the wave distribution around a ship hull may let us distinguish and establish really accurate computational methods. That is why efforts for the unsteady wave pattern measurement which are referred to above are all for this purpose.

A part of the findings of our study of the experimental and theoretical unsteady wave pattern was published already but some are not. On this opportunity we review our study concentrating on the findings not published before and some problems yet puzzling us. The abstract of them is given below.

2 Wave pattern at a great distance

The unsteady wave pattern of radiation and diffraction generated at a great distance behind a ship cruising at a constant speed was studied first by Eggers (1957). Systematic work including the analysis near the cusp (the caustics) of the wave pattern, however, had not been done before Iwashita (1990). This work was successful in treating with the surface elevation near the cusp for a wave system of shorter wave components with introducing Hogner's approach (1922). But for longer wave system it did not provide satisfactory result for the wave elevation near the cusp. We present a new analysis of this wave system following an approach proposed for the analysis of the steady wave pattern (Ursell, 1959) and attempt to give a complete asymptotic solution of the unsteady wave pattern at a great distance behind a ship. The result of the measured wave pattern will be discussed against the asymptotic one.

3 The Kochin function

Measured unsteady wave pattern is Fourier-transformed to study a linear structure of radiation and diffraction waves of a ship at forward speed. The transformation produces the Kochin function of the unsteady wave pattern i.e. amplitude of wave component propagating into each direction from the ship. The weighted integral with respect to the direction gives added resistance. The value of added resistance thus 'measured' will be added resistance in the true sense of the definition as a wave-making resistance.

In order to confirm the accuracy of this analysis the Fourier analysis was done two ways. One is the longitudinal cut analysis done for wave data measured along a line parallel to the ship track and the other is the transverse cut for the data measured transversely to the ship direction.

The former is convenient to derive the Kochin function with less experimental work. Accuracy of the analysis is investigated by doing the analysis for theoretically computed wave patterns whose Kochin function is known theoretically in advance. Comparing the 'measured' Kochin function with the theoretical one we found agreement is excellent for the longer wave-system of the pattern and the effect of the distance of the longitudinal cut line to the ship is ignorable. The 'measured' Kochin function shorter wave-system , however, is not sufficiently accurate. This is due to extreme shortness of the component waves of the shorter wave-system and partly due to insufficient resolution of the theoretically computed wave pattern. Fortunately the magnitude of the shorter wave-system is small and its contribution to added resistance is of the order of 1% of the longer system.

An error in the transverse cut technique proposed by Naitoh and Zhang (1990) was corrected by Ohkusu et al. (1994) and the result is consistent with the result of the longitudinal cut analysis; it will imply the linear structure of the unsteady wave pattern is as expected. The transverse cut gives more accurate result for high speed vessels where the wave component travelling athwart-ship is dominant. One finding here is that the transverse wave component, which is anticipated small for high speed vessels, is not small enough in the measured wave pattern to be ignored.

4 Added resistance

Added resistance is the resistance of a ship in waves minus the resistance on a calm water at the identical. A ship model is towed at a speed in a water tank by a constant force in monochromatic waves with letting its motion free. From this constant force is subtracted the resistance on a clam water measured separately, then it gives added resistance. Added resistance is a wave-making resistance produced by the disturbance given to a fluid by the ship motion and the scattering of the incident waves. Fluid viscosity naturally will contribute to it to some extent but it is understood to be small. One can 'measure' added resistance from the measured unsteady wave pattern directly without relying on the resistance test. Hereafter we specify added resistance obtained from the wave pattern as wave-pattern added resistance (WAR) and the one from the resistance test as just added resistance (AR).

It was found with blunt bow hull forms that WAR is much smaller than AR. Discrepancy apparently is large beyond explainable as a viscous effect; for some hull forms (wide and shallow form in particular) AR is several times larger than WAR. Our study has disclosed that this difference is consistently correlated to the draft-to-length ratio and the breadth-to-length ration of the hull forms.

Nakamura et al. (1983) speculated reason of this large discrepancy might be that a part of radiation and diffraction waves break near the hull form and all their energy does not reach to the far field where the wave pattern is measured. It is a rather natural speculation because it is well known that wave breaking component exists of the wave resistance on calm water. To confirm this speculation they measured the wake at the location of a half ship-length behind the stern of a hull form towed at a constant speed and forced to pitch. Comparing the wake distribution when it runs with and without the pitch motion they discovered the wake with the pitching motion is considerably larger than without the pitch It was understood that energy of the radiation waves dissipated by the breaking occurring near the hull is transformed to the momentum loss in the wake. However it has not been attempted ever since to confirm that this speculation is quantitatively correct; the measured momentum loss does not appear to be large enough to explain the difference of AR and WAR. It is not easy to achieve sufficient accuracy in the measurement of the steady wake in the unsteady flow. Further experimental work will be necessary.

Despite the practical importance of added resistance argued recently the problem of the large discrepancy between AR and WAR has never been settled theoretically. One resolution will be to develop a computational method correctly accounting for nonlinear effect and predicting added resistance larger than expected in linear theories. One finding of our observation of the wave field around a ship, which will be relevant to the resolution of the problem, is interaction of the steady and unsteady wave pattern

What is subtracted to derive AR may not be the resistance on calm water but the resistance caused by the steady wave generation when the ship runs in waves; the latter will be different from the former if the steady wave generation in waves is interacted with the unsteady wave generation. An experiment for the radiation wave of S175 (pitching) shows that this interaction exists: the larger amplitude of the pitch induces the higher steady wave height at the bow in particular

5 Comparison of the measured and computed wave pattern

Argument on added resistance stated in the previous section leads us naturally to a hope that our current computational methods of wave-body interaction may be able somehow to settle the problems.

We employed potential flow solvers based boundary element approach in the frequency domain, which are a little classical but supposed to give stable results of the unsteady wave pattern. They are Rankine Panel method, one is a method assuming simply uniform flow as the basic steady flow and the other a method based on the double model flow (the details of the computational technique are omitted for the sake of brevity). Comparison of the computed and the measured unsteady wave pattern was done mainly with diffraction wave of Series 60 ($C_B = 0.80$) model and another of more bluff bow.

We found either of two computational methods gives accurate prediction of the unsteady wave pattern if we are concerned with the wave pattern away from the bow part. Nevertheless the predicted height of the unsteady wave near the bow part (within 20 percent of ship length from the bow) is much lower than the measured. The stronger effect of the high steady wave elevation at the bow is envisaged; we tried another computational method that accounts for the effect of the steady wave elevation more accurately, a method satisfying the free surface condition of the unsteady flow on the elevated steady surface which is computed by imposing the full nonlinear free surface condition. This method either is unable to make up for the discrepancy of the unsteady wave height at the bow region.

6 Evolution of the incident waves

One concern when we measure the unsteady wave pattern around a ship is how to remove the effect of the incident regular waves. Effect of the steady Kelvin wave is removed without difficulty because it is steady and distinguishable from the unsteady part.

We extrapolate the incident waves measured far forward the the ship model since the incident waves are impossible to be measured separately at the location of the ship model. And the extrapolated time series are subtracted from the wave record. As a calibration we compared the extrapolated with the actually measured when the ship model removed. What we found is that the period of the regular waves generated in the water tank, if the wavelength is as short as $1m$ and relatively steep, gradually and slightly lengthens as the wave propagates. This evolution of the regular incident waves is slight but affects the measured unsteady wave pattern the more the longer time of extrapolation. To avoid the error we should measure the incident regular wave as close as possible to the ship model to extrapolate for experiment at relatively short wave. It will be one uncertainty at our measurement of diffraction wave.

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Steinmann et al. 1. Unsteady wave pattern generation by water striders. Thomas Steinmann1â€ , Maxence Arutkin2, PrÂ´ecillia Cochard1,3, Elie RaphaÂ¨el2, JÂ´erË†ome Casas1 and Michael Benzaquen4â€¡. 1Institut de Recherche sur la Biologie de lâ€™Insecte, UMR CNRS 7261, UniversitÂ´e de Tours, France.Â Locomotion at the air-water interface reveals a number of physical phenomena. In particular, the displacement of a disturbance at the surface creates a complex wave pattern (RaphaÂ¨el & de Gennes (1996)). The waves and vortices in the striderâ€™s wake are the signature of the momentum applied to the water. Other insects produce waves upstream from their bodies (Voise & Casas (2010); Xu et al. (2012); Jia et al.