A Numerical Prediction of Wash Wave and Wave Resistance of High Speed Displacement Ships in Deep and Shallow Water

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Abstract

In recent years, the design concept of high speed displacement craft, including concerns of safety and the environment due to the impact of ship generated wash wave, has received considerable attention. The influences on wave resistance and wash wave generated by high speed displacement craft have been investigated using a numerical method. Thin ship theory was used and developed in order to predict the wave pattern resistance and wave wash of slender hulls with transom sterns. In particular, the theory was extended to cover the supercritical speed range. The theory was validated for the physical wave patterns and profiles, especially in shallow water and at supercritical speeds using the experimental results. The validation included the effects of hull form parameters and depth Froude number on wave pattern resistance and wave profiles. It is found that the numerical method, based on the thin ship theory, can be satisfactorily employed as a simple and effective means of estimating wave pattern resistance and wave profiles with low computational effort.

1. Introduction

The introduction into service of ferries and other marine vehicles with higher service speeds has led to a new range of problems. The wash waves generated by such craft can impact upon safety and the environment in terms of the safety of smaller craft, people on beaches, coastal erosion and changes in the local ecology. As a result, there is a need to develop tools for predicting the ship generated near-field waves and their propagation to the far field, both for applications at the design stage and during ship operation. The work described in this paper focuses on the prediction of the near field wave system, assumed to be within 0.5 to 1.0 ship lengths from the vessel.

An extensive amount of research into the resistance and powering of high speed displacement monohulls and catamarans has been carried out at the University of Southampton for some years [1] – [5]. This work, which uses experimental and numerical techniques, has been extended to cover the prediction of the wash produced by such craft, and early results are reported in [6], [7]. Further experimental and numerical work has been carried out to provide design and validation data and a better understanding of the creation of wash, with particular emphasis on higher ship speeds in shallow water, [8].

Thin ship, or slender body, theory [5], [6] is used to describe the wave wash system. The thin ship approach provides an alternative to higher order panel methods for estimating wave resistance and, when applied strictly to slender hulls, has been found to provide a similar degree of accuracy at a fraction of the computational effort, [5]. The theory can provide a description of the component long-crested waves of the wave system in terms of their height, period and direction. These waves may then be used as input conditions for numerical wave propagation and transformation models, or applied directly to wave decay relationships which have been derived experimentally, such as those in [9], [10] and [11].

The basic thin ship theory requires modification which relate particularly to transom stern corrections. Developments and improvements in the estimation of this effect are described in the paper, together with the use of measured shallow water wave cuts to validate the numerical methods and provide example applications.

2. Basic Thin Ship Theory

The thin ship theory of wave resistance was originally introduced as a purely theoretical approach for predicting the wave resistance of a ship by J.H. Michell in 1898 [12]. The
background and development of the theory is described in [1], [4] and [8]. In the theory, it is assumed that the ship hull(s) will be slender, the fluid is inviscid, incompressible and homogeneous, the fluid motion is steady and irrotational, surface tension may be neglected and that the wave height at the free surface is small compared with the wave length. For the theory in its basic form, ship bodies are represented by planar arrays of Kelvin sources on the local hull centreline, together with the assumption of linearised free surface conditions. The theory includes the effects of a channel of finite breadth and shallow water.

The strength of the source on each panel may be calculated from the local slope of the local waterline, Equation (1)

$$\sigma = \frac{-U}{2\pi} \frac{dy}{dx} dA$$

Equation (1)

$$\zeta = \sum_{m=0}^{\infty} \left[ \xi_m \cos(\theta_m) + \eta_m \sin(\theta_m) \right] \cos(m \frac{\pi}{2} y)$$

Equation (2)

$$\frac{\zeta_{ref}}{\eta_{ref}} = \frac{16 \pi U}{\rho g} \sum_{m=0}^{\infty} \frac{k_0 + k_m \cos^2 \theta_m}{1 + \sin^2 \theta_m - k_m \text{sech}^2(k_m H)} \sum_{\sigma} \sigma \sigma e^{-k_m \cos^2(k_m (H + \zeta_m))} \cos(k_m \cos \theta_m) \cos(m \frac{\pi}{2} y) \cos(m \frac{\pi}{2} y)$$

Equation (3)

$$R_{wp} = \frac{\rho g \pi W}{4} \left[ \left( \xi_0^2 + \eta_0^2 \right) \left( 1 - \frac{2k_0 H}{\sinh(2k_0 H)} \right) + \sum_{m=0}^{\infty} \left( \xi_m^2 + \eta_m^2 \right) \left[ 1 - \frac{\cos^2 \theta_m}{2} \left( 1 + \frac{2k_m H}{\sinh(2k_m H)} \right) \right] \right]$$

Equation (4)

3. Transom Stern Corrections

As described above, thin ship theory represents a body with a source-sink distribution over the centreplane of the hull. The calculated source strength in each panel depends on the slope of the waterline (dy/dx). For a ship with a transom stern, the waterline slope on the transom is, therefore, undefined causing the under-prediction of wave resistance and wave wash. As a result, there is need for a transom correction to improve the potential for predicting wave resistance and wave wash.

The use of sources / sinks placed in the vicinity of the transom, [14], [15], has been used with reasonable success, whilst the creation of a virtual stern and associated source strengths, [4] and [5], has been found to provide the best results in terms of wave pattern resistance. In order to confirm
that this would also be the case for the prediction of wash waves, an investigation was carried out to verify the use of a virtual stern and/or the alternative use of source/sink placements, [8]. It was found that the use of virtual stern can provide satisfactory wave wash predictions.

With regard to a single source method, the effect of the position of a single source on the wave profile and wave pattern resistance was investigated. Source strength of a single source is equated to the strength necessary to bring the total integration of source/sink strength over the hull to zero. The best results were obtained using a single source near the base of the transom, when the correlation with the experimental results was seen to be good [8]. This approach is much simpler to apply than a virtual stern. A single source approach was, therefore, used for validation of the theory to model transom correction.

4. Validation of the Theory and Example Applications

4.1 General

Examples are presented to validate the theory and to illustrate its applications and scope. The theory has been well validated for wave pattern resistance in deep water, [4], [5] and [15]. Validation of the theory was required for the physical wave patterns and profiles, especially in shallow water and at supercritical speeds. This has been facilitated using the new shallow water experimental data presented in [8]. The hull forms used in the investigations are shown in Fig.2 and their particulars are given in Table 1.

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Table 1: Principal particulars of models

4.2 Round bilge catamaran hull, Series 64, Deep water: theoretical and experimental

A number of physical wave cuts for the Series 64 model had been carried out in the Southampton Institute test tank. Comparisons of the theoretical and experimental wave cuts are shown in Fig.3. It is seen that there is reasonable agreement between the theoretical and experimental results.

4.3 Round bilge monohull, NPL Series, Shallow water: subcritical - theoretical and experimental

Fig.4 shows the comparison of measured and predicted wave cuts for model 5b at Froude Numbers Fn of 0.22 and 0.38 at a water depth of 0.4m. It is seen that acceptable agreement is achieved.

4.4 Round bilge catamaran hull, NPL Series, Shallow water: supercritical - theoretical and experimental

Fig.5 shows a comparison of the measured and predicted wave cuts for model 5b for different water depths (H=0.2m and 0.4m) and two hull separations (S/L=0.2 and 0.4). In general, the theory provides an acceptable agreement with the experiments, especially at very high speeds. The theory with no transom correction underestimates the wave height, whilst the theory with a single source correction gives better results, including the prediction of the leading bow waves. It is however found that, at supercritical speeds, the theory with a single...
source tends to create a hollow in front of the bow wave, although the size of the hollow decreases with increase in $F_n$.

4.5 Effect of Length/Displacement ratio ($L/\sqrt[3]{\nu}$)

Fig. 6a shows the influence of $L/\sqrt[3]{\nu}$ on the wave pattern resistance. It is seen that an increase in $L/\sqrt[3]{\nu}$ causes a reduction in wave pattern resistance, which is in line with the experimental results in Fig. 6b. Fig. 7 shows good agreement between the experimental and theoretical wave cuts for model 4b ($L/\sqrt[3]{\nu} = 7.4$) and model 5b ($L/\sqrt[3]{\nu} = 8.5$).

4.6 Effect of Catamaran hull separation ($S/L$), in shallow water

Fig. 8 shows the influence of catamaran hull separation on the wave pattern resistance. It is seen that as the separation is increased, there is a reduction in resistance, which is in line with the experimental results. Fig. 9 shows good agreement between the experimental and theoretical wave cuts for the two separations.

4.7 Theoretical wave pattern resistance

Fig. 10 shows the theoretical estimates of the wave pattern resistance ratio (wave pattern resistance shallow water/wave pattern resistance deep water) for model 5b catamaran with $S/L = 0.2$ at water depths of $H = 0.2m$ and $0.4m$ for a range of depth Froude Number. It is seen that the trend agrees with the experimental results, although the theoretical ratio at about
critical speed is much higher than the experimental results. It is noted that the effects of shallow water are significant in the critical speed region, where there are large increases in resistance, whilst the resistance decreases again at supercritical speeds.

Fig.10 Experimental and theoretical wave resistance ratio: Model 5b catamaran S/L=0.2

4.8 Divergent wave angle

Fig.11 shows the change in divergent wave angle with change in speed, derived using Kofoed-Hansen theory, [11], the thin ship theory and the experimental results [8]. It is seen that there is good agreement between the thin ship theory and the experimental results.

Fig.11 Diverging wave angle

4.9 Distribution of wave energy

Predicted wave patterns and the distribution of the wave pattern resistance components (or wave energy) at different water depths are shown in Fig.12.

It is seen that at supercritical speeds, since a gravity wave cannot travel at speeds > (gH)^1/2, the transverse waves disappear and waves can only be propagated at angles greater than θ = \cos^{-1}\left(\frac{gH}{U}\right)^{1/2}.

These results, which describe wave patterns and their associated distribution of wave components (or energy) within that pattern, together with the prediction of the wave propagation angles (Fig.11), are of value as input to wave propagation models.

Fig. 12 Wave pattern & distribution of wave pattern resistance: change in depth Froude number at a given speed (Fn=0.5), Model 5b monohull.
4.10 Summary
The chosen examples have illustrated the wide scope and usefulness of theoretical methods in the prediction of wave patterns and wave wash and, in particular, the relative effects due to changes in the design and operational features. This has allowed the development of a robust numerical method, based on thin ship theory, suitable for the estimation of near field wash waves in terms of wave period, height, direction of propagation and energy distribution, in a form suitable for use in wave propagation/transformation models.

5. CONCLUSIONS
5.1 The numerical method which has been developed offers a practical tool for assessing the likely wave wash of new designs, together with operational effects on the wash of ships in service.
5.2 The theoretical results, validated by experiments, provide the facility to develop low wash guidelines for operational features such as speed, trim and shallow water, and low wash design features such as the influences of $L/\sqrt{\lambda}$, S/L and hull shape.
5.3 Overall, it is found that the numerical methods developed and described provide very realistic predictions of wave wash and wave resistance.

6. Acknowledgements
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References