Illustrative applications of the Neumann-Michell theory of ship waves

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Introduction

The modification of the classic Neumann-Kelvin (NK) theory of ship waves, called Neumann-Michell (NM) theory, expounded in [1] is considered. A main difference between the NK and NM theories is that the NM theory does not involve a line integral around the ship waterline. This waterline integral, a well-known prominent feature of the NK theory, is eliminated in the NM theory by removing an inconsistency in the linearization that underlies the NK theory (which does not correspond to a consistent linear flow model) and, furthermore, by using a mathematical transformation (essentially an integration by parts).

A notable property of the NM theory is that it defines the flow around a ship hull (steadily advancing in calm water) as a correction to the classic slender-ship approximation proposed by Hogner. Specifically, the NM theory of ship waves given in [1] expresses the (nondimensional) flow potential $\widetilde{\phi}$ at a flow field point $\widetilde{\mathbf{x}}$ as the sum of the Hogner slender-ship approximation $\widetilde{\phi}_H$, which is defined explicitly in terms of the Froude number and the hull geometry, and a correction potential $\widetilde{\psi}^W$ that modifies the waves contained in the Hogner approximation $\widetilde{\phi}_H$. A main property of the NM correction $\widetilde{\psi}^W$ is that it involves the flow velocity components $\phi_d \equiv \partial\phi/\partial d$ and $\phi_t \equiv \partial\phi/\partial t$ along the two orthogonal unit vectors $\mathbf{d} \equiv (0, -\nu^z, \nu^y)$ and $\mathbf{t} \equiv (\nu, -n^x\nu^y, -n^x\nu^z)$ that are tangent to the ship hull surface Σ^H. Here, $\mathbf{n} \equiv (n^x, n^y, n^z)$ is a unit vector that is normal to Σ^H and points outside the ship (into the water), $(\nu^y, \nu^z) \equiv (n^y, n^z)/\nu$ and $\nu \equiv \sqrt{(n^y)^2 + (n^z)^2}$. Within the NM theory given in [1], the flow potential $\widetilde{\phi}$ at a point $\widetilde{\mathbf{x}}$ of the hull surface Σ^H is then determined by the solution of an integro-differential equation $\widetilde{\phi} = \widetilde{\phi}_H + \widetilde{\psi}^W(\phi_t, \phi_d)$ with $\widetilde{\mathbf{x}} \in \Sigma^H$. A straightforward iterative solution procedure $\widetilde{\phi}^{k+1} \approx \widetilde{\phi}_H + \widetilde{\psi}^W(\phi_t^k, \phi_d^k)$ with $\widetilde{\mathbf{x}} \in \Sigma^H$, $0 \leq k$ and $\phi^0 \equiv 0$ is used. The first approximation $\widetilde{\phi}^1$ in the sequence of approximations $\widetilde{\phi}^k$ to the NM potential $\widetilde{\phi} \equiv \widetilde{\phi}^\infty$ is the Hogner potential $\widetilde{\phi}_H$. Thus, the NM theory provides a way of correcting the classic Hogner approximation.

An important aspect of the NM theory is considered in [2], which gives a highly simplified analytical approximation for the local flow component in the Green function that satisfies the radiation condition and the Kelvin-Michell linearized boundary condition at the free surface. Another important element, indeed a critical one, of the NM theory is considered in [3]. There, the dual basic tasks of evaluating the wave potential $\widetilde{\phi}_H^W + \widetilde{\psi}^W$ at the free surface $\widetilde{z} = 0$ and of removing unrealistic or inconsequential short waves is considered. Briefly, within a thin layer bordering the mean free-surface plane $z = 0$, waves are evaluated in [3] using a physics-based filter, based on parabolic extrapolation in the vicinity of the free surface, that accounts for fundamental differences between a ship bow wave and waves aft of the bow wave. A third basic aspect of the NM theory, considered in [4], is the evaluation of the derivatives ϕ_t and ϕ_d that appear in the NM wave potential $\widetilde{\psi}^W(\phi_t, \phi_d)$. This issue is important because the solution of the NM integro-differential equation is significantly affected by the numerical approximation of the derivatives ϕ_t and ϕ_d, particularly within the framework of a low-order panel approach and for full hull forms. Numerical implementation of the NM theory, within the practical framework of a low-order panel method, is considered in [4], where illustrative applications to eight ship hulls are also reported.

Comparison of independent numerical predictions for the Wigley hull

Numerical predictions given by the NM theory are reported in [1,3] for the Wigley hull and the Series 60 model. Fig.1 compares these numerical predictions (obtained by the first author at GMU) for the Wigley hull and the numerical predictions (obtained by the second author at HEU) using an independent numerical implementation of the theory. The two numerical implementations are based on the same mathematical expressions. Furthermore, both use a low-order panel approach and an iterative solution procedure that iteratively improves upon the Hogner initial approximation. Thus, the numerical results can be expected to be close, but not necessarily identical due to differences in the first two authors' independent numerical implementations. Fig.1 shows good agreement between the independent numerical implementations for the sinkage, trim, and drag predicted by the NM theory for the Wigley hull. Thus, Fig.1 provides a useful verification of the numerical results given in [1,3]. However, significant discrepancies can be observed in Fig.2 for the wave profiles along the Wigley hull. These discrepancies, due to differences in the evaluation of the flow velocity $\nabla\phi$, illustrate the fact that mathematical expressions like those given in [1-3] are not sufficient to fully determine a theory. Indeed, precise information about the numerical implementation of mathematical expressions is also required, and this important aspect of the theory is considered in [4].

Illustrative applications to four ship hulls

Numerical predictions given by the NM theory are reported in [4] for eight ship hulls. Here, we consider the four hull forms depicted in Fig.3. These hulls are the Wigley hull (top row), the Series 60 ($C_b = 0.60$) model (second row), the DTMB-5415 model (third row) and the KCS model (bottom row). Experimental measurements for these four hulls are reported in [5-8]. Fig.4 compares experimental measurements of the wave drag, reported in [5-8], and predictions of the nearfield wave drag (determined via integration of the flow pressure at the ship hull surface) and of the farfield wave drag (determined via the Havelock formula) for the hulls in fixed position (no sinkage or trim is considered in the calculations).

Conclusion

A positive and encouraging finding, at this stage of the development and application of the NM theory, is that a straightforward low-order panel implementation of the theory yields robust predictions for a broad range of ship hulls, and that these theoretical predictions are reasonable and realistic. The finding is notable in view of the remarkable simplicity of the theory, which is based on linear potential flow, does not involve a line integral around the ship waterline, amounts to the addition of a simple correction (the wave potential $\widetilde{\psi}^W$ mentioned in the introduction) that modifies the waves predicted by the classic Hogner slender-ship approximation, uses a highly-simplified Green function, and only involves staightforward Gaussian integration of elementary continuous functions. The short-wave filter and the numerical smoothing of the derivatives ϕ_d and ϕ_t given in [4] are critical elements of the theory.

Much work evidently remains to be performed before the merits and limitations of the NM theory can be fully ascertained. This work includes (i) evaluation of the flow (notably wave patterns) outside the ship hull, (ii) consideration of elementary nonlinear corrections that can be incorporated to improve the predictions given by the NM linear theory, (iii) account for sinkage and trim effects, ignored so far, which are particularly important to predict the sinkage and trim experienced by a moving ship hull, (iv) account for the viscous boundary layer and wake in accordance with the classical theory of high-Reynolds number flows around streamlined bodies, and (v) applications to a much broader set of ship hulls than the four hulls considered here and the eight hulls considered in [4]. This ongoing work will be reported as it is completed.

Acknowledgments

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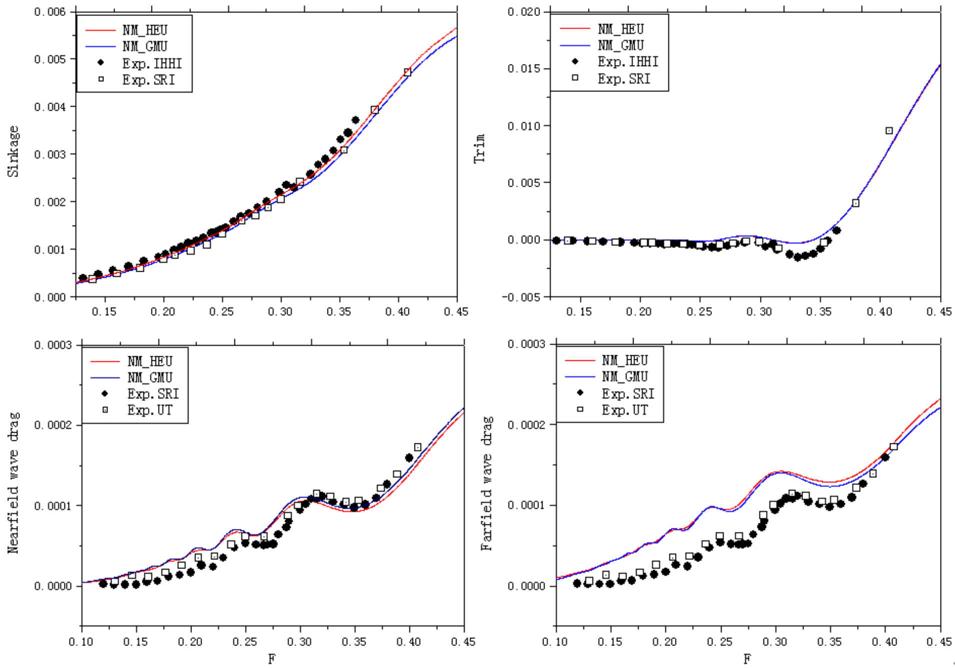

Figure 1: Experimental measurements (Exp.) and theoretical predictions, based on the NM theory (NM) and obtained at George Mason Univ. (GMU) and Harbin Engineering Univ. (HEU), of the sinkage (top left corner), trim (top right), nearfield wave drag (bottom left) and farfield wave drag (bottom right) for the Wigley hull.

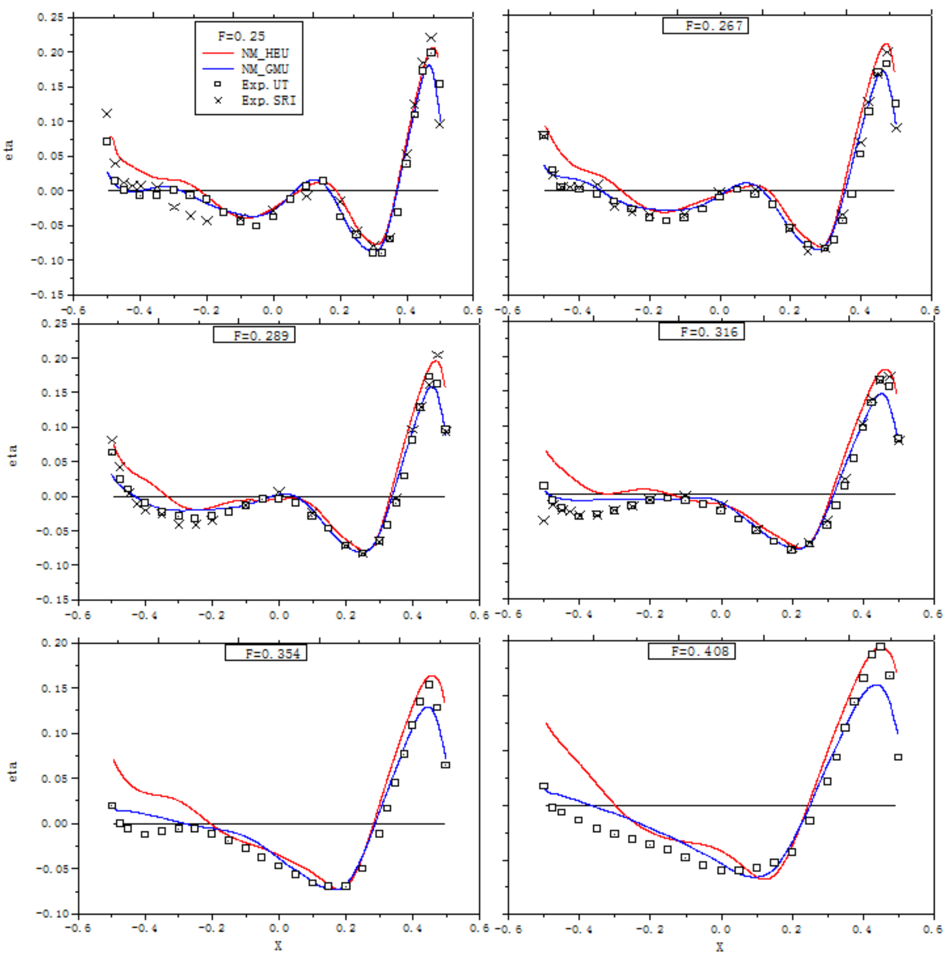

Figure 2: Experimental measurements (Exp.) and theoretical predictions, based on the NM theory (NM) and obtained at George Mason Univ. (GMU) and Harbin Engineering Univ. (HEU), of wave profiles along the Wigley hull at six Froude numbers $F = 0.25$, 0.267, 0.289, 0.316, 0.354 and 0.408.

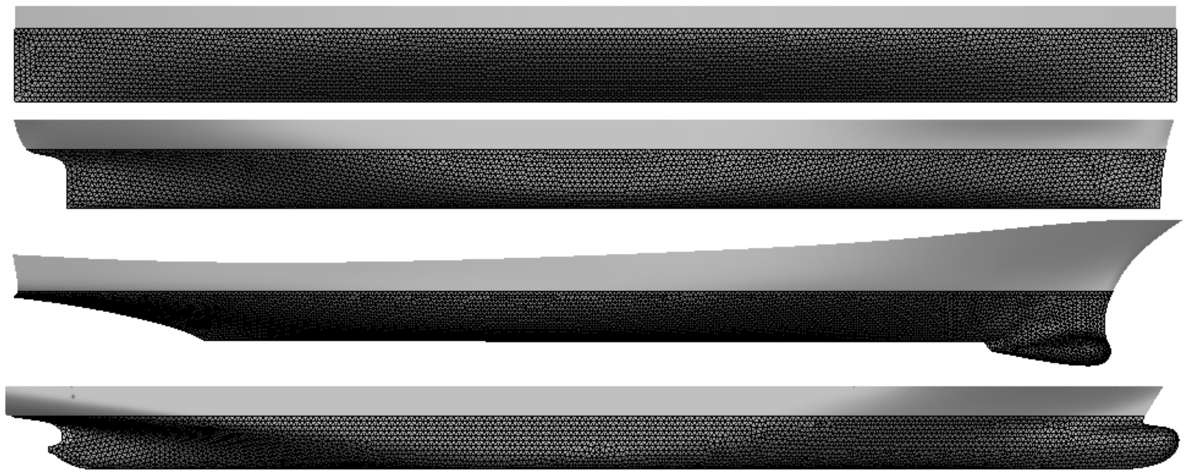

Figure 3: Side views, with meshes over the mean wetted hull surfaces, of the Wigley hull (top row), the Series 60 $C_b = 0.60$ model (second row), the DTMB-5415 model (third row) and the KCS model (bottom row). The positive halves of these four hull surfaces are approximated using 8,000 flat triangular panels for the Wigley hull and the Series 60 model, 9,600 panels for the DTMB-5415 model, and 18,960 panels for the KCS model (fewer panels are shown in the figure for clarity).

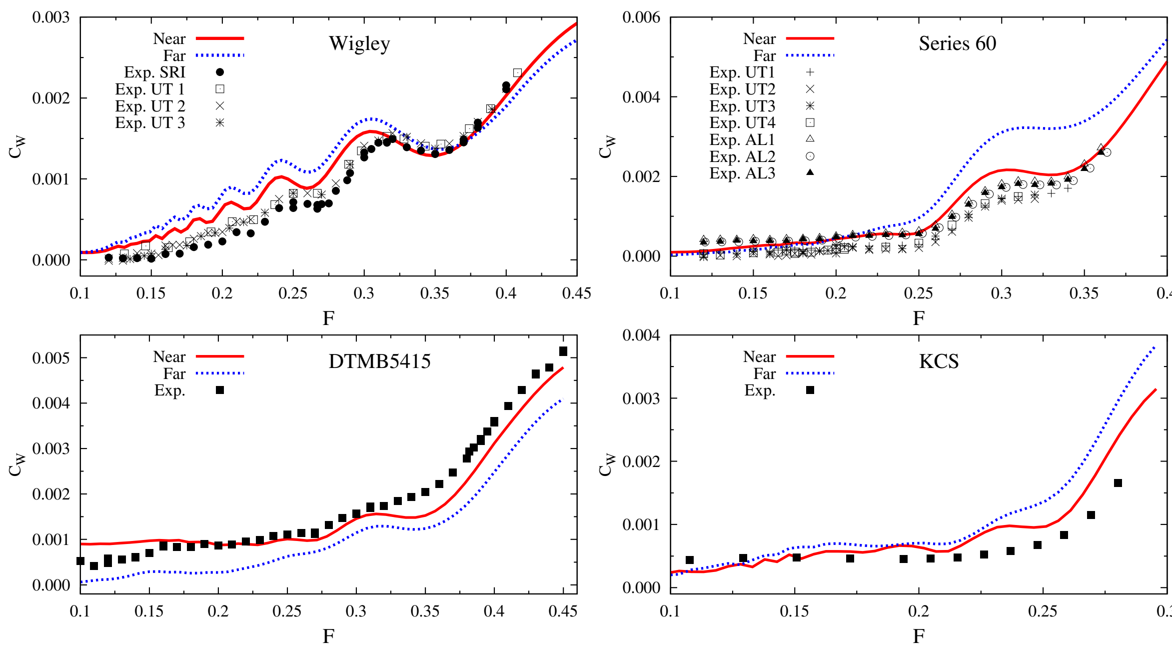

Figure 4: Experimental measurements (Exp.) of the wave drag, and nearfield (Near) and farfield (Far) wave drags predicted by the NM theory, for the Wigley hull (top left corner), the Series 60 $C_b = 0.60$ model (top right), the DTMB-5415 model (bottom left) and the KCS model (bottom right). For the experimental measurements shown here, the Wigley hull and the Series 60 model are held fixed (no sinkage or trim is allowed), but the DTMB-5415 and KCS models are unrestrained (sinkage and trim are allowed). No sinkage or trim is considered in the NM calculations.