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Nonlinear corrections of linear potential-flow theory of ship waves

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HIGHLIGHTS

- Nonlinear effects on sinkage, trim, wave drag and wave profiles are relatively small.
- An important exception is the wave drag of ships with bulbous bows.
- Predictions of NM theory with nonlinear corrections agree well with experiments.

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ABSTRACT

The Neumann–Michell (NM) theory – a practical linear potential flow theory – is applied to four freely-floating ship models (Wigley, S60, DTMB5415, KCS), assumed to advance at a constant speed in calm water of large depth, to investigate nonlinear effects on the wave drag, the sinkage, the trim, and the wave profile along the hull, and to approximately account for these effects via simple corrections of the linear theory. Nonlinear effects are found to be relatively small. However, an important exception to this general finding is that the wave drag of a bulbous ship (DTMB5415, KCS) is greatly reduced due to the nonlinear component of the pressure in the Bernoulli relation. This important nonlinear effect is readily included in the NM theory. The nonlinear component of the pressure in the Bernoulli relation also yields a small increase of the sinkage, likewise readily included in the NM theory. Moreover, free-surface nonlinearities can have appreciable, although not large, effects on the wave profile. These nonlinear effects can also be approximately taken into account via a simple transformation of the linear wave profile. Indeed, the flow computations for the four ship models considered here suggest that simple (post-processing) nonlinear corrections (that require no additional flow computations) of the NM theory yield numerical predictions of the wave drag, the sinkage, the trim and the wave profile that agree well with experimental measurements, and compare favorably with predictions given by more complex computational methods.

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1. Introduction

Nonlinear effects on the flow around a ship that advances at a constant speed in calm water of large depth and lateral extent are considered. The influence of nonlinearities is readily apparent from a ship bow wave, where wavebreaking or overturning thin sheets of water are commonly observed [1,2]. Such nonlinear effects cannot be directly modeled within the framework of linear potential flow theory. In particular, linear potential flow theory cannot predict the occurrence of wavebreaking, although it arguably may be less ill suited than nonlinear potential flow theory to represent highly nonlinear effects associated with wavebreaking or overturning waves at a ship bow. Wavebreaking can in principle be modeled within the framework of CFD methods that solve the unsteady Reynolds-averaged Navier–Stokes equations (URANS), although the difficulties are considerable. Moreover, CFD methods based on the URANS are ill suited and unnecessary for routine practical applications to ship design and hull-form optimization, for which linear potential flow theory is adequate and most useful. Indeed, linear potential flow theory – specifically the Neumann–Michell (NM) theory considered here – is practical and yields predictions of the sinkage, the trim, the drag and wave profiles that are in satisfactory agreement with experimental measurements as well as numerical predictions obtained via alternative, considerably more complex, computational methods, as is shown in several studies listed below.

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The NM theory is based on the usual Kelvin–Michell linearized free-surface boundary condition. Main features of that theory, expounded in [3,4], are summarized in [5] and are only briefly noted here. The NM theory is a modification of the well-known Neumann–Kelvin (NK) theory. In particular, the NM theory does not involve a line integral around the ship waterline, unlike the NK theory, and is based on a consistent linear flow model, whereas [3] argues that the NK theory does not correspond to a consistent linear flow model. Main features of the NM theory are considered in [6–9], and validation studies and applications are reported in [4,5,10–14]. In particular, [14] shows that the influence of sinkage and trim on the drag of a common monohull ship at Froude numbers $F \leq 0.45$ can easily and realistically be evaluated via the NM theory. A notable useful feature of this theory is that it is well suited for routine practical applications to ship design and hull-form optimization, as is amply demonstrated in [15–23]. Indeed, the NM theory yields realistic flow predictions, sufficiently accurate for hydrodynamic optimization, in a very practical way. In particular, the NM theory makes it possible to evaluate the pressure distribution at a ship hull surface in about 1s using a common PC.

This practical linear potential flow theory is used here to analyze the influence of nonlinear effects on the sinkage, the trim, the wave drag and the wave profile along the ship hull, and to approximately account for these nonlinear effects via simple corrections of the linear theoretical predictions (without additional flow computations). Nonlinear effects on the wave drag, the trim, the sinkage and the wave profile are found to be relatively small. An exception to this general finding is that the wave drag of a ship with a large bulb is greatly reduced due to the nonlinear component of the pressure in the Bernoulli relation. This important nonlinear effect on the wave drag is readily taken into account within the NM theory. In addition, the nonlinear component of the pressure in the Bernoulli relation yields an increase of the sinkage. This relatively small but appreciable nonlinear effect is also readily included within the NM theory. Moreover, free-surface nonlinearities can have appreciable, although not large, effects on the wave profile. These nonlinear effects on the wave profile can also be approximately taken into account via a simple correction of the linear wave profile.

Four freely-floating ship models (Wigley, S60, DTMB5415, KCS) are considered here for purposes of illustration and validation. Side views and bottom views of these four well-known models are depicted in Fig. 1. Numerical predictions of the sinkage, the trim, the wave drag and wave profiles are compared with experimental measurements reported in the literature.

Specifically, for the Wigley hull, the six sets of experimental measurements of sinkage, trim and residuary drag performed at IHHI (Ishikawajima-Harima Heavy Industries), SRI (Ship Research Institute), UT (University of Tokyo) and YNU (Yokohama National University), and the two sets of experimental measurements of wave profiles at six Froude numbers within the range $0.25 \leq F \leq 0.408$ performed at UT and SRI, are used here. These experimental measurements are reported in [24–26].

For the S60 ship model, the seven sets of measurements of sinkage, trim and residuary drag performed at IHHI, UT, SRS (Ship Research Station), UH (University of Hiroshima) and SSSRI (Shanghai Ship & Shipping Research Institute), and the three sets of measurements of wave profiles at eleven Froude numbers within the range $0.18 \leq F \leq 0.35$ performed at UT, SRS and SNU (Seoul National University), are used. These experimental data are reported in [26–28].

For the DTMB5415 model, the three sets of measurements of sinkage, trim, residuary drag and wave profiles (for $F = 0.28$ and $F = 0.41$) performed at DTMB (David Taylor Model Basin), INSEAN (Instituto Nazionale Per Studi Ed Esperienze Di Architettura Navale) and IIHR (Iowa Institute of Hydraulic Research) and reported in [29–31] are used.

Finally, for the KCS ship model, the two sets of measurements of sinkage, trim and residuary drag performed at MOERI (Maritime Ocean Engineering Research Institute) and NMRI (National Maritime Research Institute) and reported in [29–31], and the experimental wave profiles (for $F = 0.26$) measured at MOERI and reported in [32,33], are used.

The flow computations for the four ship models considered here suggest that simple (post-processing) nonlinear corrections (that require no additional flow computations) of the NM linear theory yield numerical predictions of the wave drag, the sinkage, the trim and the wave profile that agree well with experimental measurements, and compare favorably with predictions given by more complex computational methods.

2. Pressure

Potential flow around the mean wetted hull surface Σ^H of a ship, of length L, that advances at a constant speed V in calm water of effectively infinite depth and lateral extent is considered. Coordinates and flow variables are made nondimensional with respect to the gravitational acceleration g, the water density ρ, and the length L and the speed V of the ship. The Froude number is defined as $F \equiv V/\sqrt{gL}$. The flow is observed from a Cartesian system of nondimensional coordinates $\mathbf{x} \equiv (x, y, z) \equiv \mathbf{X}/L$ attached to the moving ship, and is then steady (independent of time). The x axis is chosen along the path of the ship and points toward the ship bow. The undisturbed free surface is taken as the plane $z = 0$ and the z axis points upward. The ship bow and stern are located at $(0.5, 0, 0)$ and $(-0.5, 0, 0)$. The flow velocity is given by $(\phi_x - 1, \phi_y, \phi_z)$ where $(\phi_x, \phi_y, \phi_z) \equiv (\Phi_X, \Phi_Y, \Phi_Z)/V$ denotes the velocity of the flow created by the ship and $\phi \equiv \Phi/(VL)$ is the flow potential. The unit vector $\mathbf{n} \equiv (n^x, n^y, n^z)$ is normal to the ship hull surface Σ^H and points outside the ship (into the water).

The nondimensional flow pressure p at the ship hull surface Σ^H is determined from the Bernoulli relation

$$p \equiv (P - P_a)/(\rho V^2) = p^* - z/F^2 \tag{1a}$$

where P_a denotes the atmospheric pressure, and p^* is the hydrodynamic pressure

$$p^* = \phi_x - (\phi_x^2 + \phi_y^2 + \phi_z^2)/2. \tag{1b}$$

The linear approximation ϕ_x to the pressure p^* is denoted as $\widetilde{p^*} \equiv \phi_x$ hereafter.

The velocity components (ϕ_x, ϕ_y, ϕ_z) at a ship hull surface Σ^H can be expressed in terms of the velocity component ϕ_n along the unit vector $\mathbf{n}$ normal to Σ^H and the velocity components ϕ_d and ϕ_t along two unit vectors $\mathbf{d}$ and $\mathbf{t}$ tangent to Σ^H. The unit vectors $\mathbf{d}$ and $\mathbf{t}$ are chosen as

$$\mathbf{d} \equiv \frac{[\,0, -n^z, -n^y\,]}{\sqrt{(n^y)^2 + (n^z)^2}} \quad \text{and} \quad \mathbf{t} \equiv \frac{[(n^y)^2 + (n^z)^2, -n^x n^y, -n^x n^z\,]}{\sqrt{(n^y)^2 + (n^z)^2}}$$

here, as in [3]. The three unit vectors $\mathbf{n}$, $\mathbf{d}$ and $\mathbf{t}$ are orthogonal. One then has

$$\phi_x^2 + \phi_y^2 + \phi_z^2 = \phi_n^2 + \phi_t^2 + \phi_d^2 = (n^x)^2 + \phi_t^2 + \phi_d^2$$

where the boundary condition $\phi_n = n^x$ at Σ^H was used, and

$$p^* = \sqrt{(n^y)^2 + (n^z)^2}\,\phi_t + (n^x)^2/2 - (\phi_t^2 + \phi_d^2)/2 \tag{2a}$$

$$\widetilde{p^*} = \phi_x = \sqrt{(n^y)^2 + (n^z)^2}\,\phi_t + (n^x)^2. \tag{2b}$$

The tangential velocity components ϕ_t and ϕ_d are determined hereafter via the Neumann-Michell (NM) theory, as was already

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