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Analytical relations for filtering negligible short ship waves

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ABSTRACT

The important basic practical problem of filtering inconsequential short waves that have no significant influence upon the wave drag, the sinkage and the trim experienced by a ship that travels at a constant speed in calm water of large depth is considered. This problem is an essential and nontrivial element of the prediction of ship waves via the use of a Green function that satisfies the linearized boundary condition at the free surface. Simple analytical relations that explicitly determine the wavenumber of insignificant short waves in terms of the Froude number and three main parameters that broadly characterize the ship hull shape are given for ships with bow, midship and stern regions and for ships with wide transoms. These relations are obtained via a parametric numerical analysis, based on the classical Hogner potential flow model, for a wide range of Froude numbers and a large number of hull forms associated with a broad range of hull-shape parameters. The relations provide an effective way of filtering negligible short waves that have no appreciable influence upon the wave drag, the sinkage and the trim of a ship.

1. Introduction

The flow around a ship of length L that travels at a constant speed V along a straight path, in calm water of large depth and horizontal extent, is considered within the classical framework of the linear potential flow theory based on a Green function that satisfies the linearized boundary condition at the free surface. This theoretical framework is realistic and indeed yields predictions of the drag, the sinkage and the trim experienced by a ship, as well as the wave profile along a ship hull, that are in satisfactory overall agreement with experimental measurements and are sufficiently accurate for practical purposes, notably for early design and hull-form optimization, within a broad range of Froude numbers, as is illustrated in e.g. [1–9]. In addition, linear potential flow theory provides a practical framework that is well suited for routine applications to ship design and hull-form optimization, as is amply demonstrated in e.g. [10–18].

Within the framework of the linear potential flow theory based on a Green function associated with the Kelvin-Michell linear free-surface boundary condition that is considered here, the flow created by the ship can be formally expressed as the sum of a non-oscillatory local flow component that vanishes rapidly away from the ship and a wave component that is dominant in the far field, and indeed also in the near field. The local flow component can be evaluated in a straightforward manner, as is shown in [19,20], and is not considered here. The ship waves can also be effectively evaluated via the classical Fourier-Kochin approach; e.g. [1,2,19].

Within this approach, ship waves are expressed as a linear Fourier superposition of elementary plane waves with wavelengths $\Lambda_{min} \le \Lambda \le \Lambda_{max}$ where $\Lambda_{min} = 0$ and

$$\Lambda_{\max} \equiv 2\pi V^2/g \tag{1}$$

is the wavelength of the longest waves created by the ship along its track. Here, g denotes the acceleration of gravity. Very short waves are affected by surface tension or viscosity. Thus, very short 'pure-gravity' waves are physically unrealistic and must be ignored. Even relatively short waves that are not appreciably influenced by surface tension or viscosity, but do not significantly affect the pressure distribution at the ship hull surface, can be eliminated. Moreover, short waves must be filtered to obtain satisfactory numerical predictions that are free from unrealistic oscillations, as is shown in e.g. [2,19,21].

Selection of the wavelength Λ_{min} of the shortest waves that must be retained within the Fourier-Kochin representation of ship waves is then an important element of the computation of ship waves within the linear potential flow theory, notably the Neumann-Michell theory expounded in [1,2], based on a Green function that satisfies the Kelvin-Michell linear boundary condition at the free surface. Furthermore, the elimination of short waves that is required to obtain satisfactory linear potential flow numerical predictions is shown in [1,2,19,21] to be a

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fairly complex issue.

A practical approach for selecting Λ_{min} is considered here. This approach relies on a parametric numerical study—based on the classical Hogner approximation to the flow around a ship hull given in [1,2,22–24]—for a broad range of Froude numbers and hull forms to determine the wavelengths $\Lambda < \Lambda_{min}$ of inconsequential short waves that have no significant influence upon the wave drag, the sinkage and the trim.

Specifically, the parametric study reported here considers Froude numbers F within the wide range

$$0.15 \leq F \equiv V/\sqrt{\mathrm{gL}} \leq 2 \tag{2}$$

and analytically-defined simple ship hulls with draft D and beam B within the broad ranges

$$0.02 \leq \frac{D}{L} \leq 0.1, \quad 0.1 \leq \frac{B}{L} \leq 0.2, \quad 0.1 \leq \frac{D}{B} \leq 1 \tag{3a}$$

Two families of ship hulls are considered. The first family of ships contains 120 hulls with a bow region, a stern region and a cylindrical midship region of lengths denoted as L_b, L_s and $L_m \equiv L - L_b - L_s$ that vary within the ranges

$$0.2 \leq \frac{L_b}{L} \leq 0.5, \quad 0.1 \leq \frac{L_s}{L} \leq 0.5, \quad 0 \leq \frac{L_m}{L} \leq 0.7 \tag{3b}$$

The second family is related to ships with wide transoms, and contains 120 hulls with a bow region and a cylindrical aftbody of lengths L_b and $L_m \equiv L - L_b$ that vary within the ranges

$$0.2 \leq \frac{L_b}{L} \leq 0.5, \quad 0.5 \leq \frac{L_m}{L} \leq 0.8 \tag{3c}$$

Unlike the first family of ships, the second family of ships does not involve longitudinal interferences between the bow wave and the stern wave.

The parametric numerical analysis considered here yields analytical expressions that explicitly determine the cutoff wavelength Λ_{min} in terms of the Froude number F and three main hull-form parameters: the draft / length ratio $d \equiv D/L$, the beam / length ratio $b \equiv B/L$, and the nondimensional length $\ell_m \equiv L_m/L$ of the midship region or, for ships with wide transoms, of the region aft of the bow region.

2. Basic relations

The flow due to the ship is observed in a system of orthogonal coordinates $\mathbf{X} \equiv (X, Y, Z)$ attached to the moving ship. The undisturbed free surface is chosen as the plane $Z = 0$ with the Z axis directed upward, and the X axis is taken along the path of the ship and directed toward the bow. The flow thus appears steady with flow velocity given by the sum of the apparent uniform current $(-V, 0, 0)$ that opposes the ship speed V and the (disturbance) flow velocity given by the gradient (Φ_X, Φ_Y, Φ_Z) of the flow potential $\Phi(\mathbf{X})$. The length L and the speed V of the ship are used to define the nondimensional coordinates $\mathbf{x} \equiv \mathbf{X}/L$, flow velocity $(\phi_x, \phi_y, \phi_z) \equiv (\Phi_X, \Phi_Y, \Phi_Z)/V$ and flow potential $\phi \equiv \Phi/(VL)$.

Within the linear potential flow analysis considered here, the flow around the ship hull is expressed in terms of a Green function $G(\mathbf{x}, \boldsymbol{\xi})$ that satisfies the radiation condition and the Kelvin-Michell linear boundary condition at the free surface $z = 0$, and represents the (nondimensional) velocity potential of the flow created at a flow-field point $\mathbf{x} \equiv (x, y, z)$ by a unit source located at a source point $\boldsymbol{\xi} \equiv (\xi, \eta, \zeta)$. The Green function G can be formally expressed as $G = L + W$ where L denotes a non-oscillatory local flow component, which can readily be evaluated via the simple global approximation given in [19,20], and W represents the waves contained in G. The flow potential $\phi \equiv \phi(\mathbf{x})$ at a flow-field point $\mathbf{x}$ can similarly be expressed as $\phi = \phi^L + \phi^W$. The local flow potential ϕ^L is ignored here as was already noted.

The wave potential $\phi^W \equiv \phi^W(\mathbf{x})$ is given by

$$\phi^W = \frac{1}{\pi}\,\mathrm{Im}\int_{-q_\infty}^{q_\infty} \Psi A\, E\mathrm{d}q \tag{4a}$$

where $E \equiv E(q, \mathbf{x})$ denotes the elementary wave function

$$E \equiv \mathrm{e}^{(1+q^2)z/F^2 + \mathrm{i}\sqrt{1+q^2}\,(x+q\,y)/F^2} \tag{4b}$$

Moreover, the finite limits of integration $\pm q_\infty$ and the function Ψ filter inconsequential short waves, and q_∞ is related to the shortest wavelength Λ_{min} mentioned in the introduction.

As was already noted, selection of a filter function Ψ in the Fourier representation (4a) of ship waves is an important and nontrivial basic issue [1,2,19,21]. However, evaluation of the integral (4a) that defines ship waves at a flow field point $\mathbf{x}$ is not required in the present study. Indeed, the study considers the Hogner approximation to the wave drag, the sinkage and the trim—defined by the integrals (21a) given further on—for ship hulls that are defined mathematically. The integrands of the integrals (21a) vanish sufficiently fast as $q \to \infty$ that there are no convergence issues for the evaluation of these integrals. Thus, the filter function Ψ in (4a) only has a minor role in the present study, although smooth decay of the function Ψ in the vicinity of q_∞ renders the numerical evaluation of the integrals (21a) more robust. The filter function Ψ is chosen here as

$$\Psi \equiv 1 - (q/q_\infty)^6 \tag{5}$$

The exponent 6 in (5) could be taken smaller or larger without appreciable consequences. Indeed, ψ could be chosen as $\Psi = 1$ for the computations of the wave drag, the sinkage and the trim considered further on.

The Fourier variable q in (4) is related to the wavenumber

$$k \equiv \mathrm{K\,L} = (1 + q^2)/F^2$$

as readily follows from (4b), and the wavelength

$$\lambda \equiv \frac{\Lambda}{L} = \frac{2\pi}{k} = \frac{2\pi F^2}{1 + q^2} \leq 2\pi F^2 \equiv \lambda_{\max} \tag{6a}$$

where $\lambda_{max} \equiv \Lambda_{max}/L$ is the wavelength of the longest waves created by a ship along its track. The relations (6a) show that the shortest wavelength Λ_{min} and the limit of integration q_∞ in the wave integral (4a) are related as

$$\frac{\Lambda_{\min}}{F^2 L} = \frac{\Lambda_{\min}}{V^2/g} = \frac{2\pi}{1 + q_\infty^2} \tag{6b}$$

The ratio $\Lambda_{min}/\Lambda_{max}$ of the shortest wavelength Λ_{min} to the longest wavelength Λ_{max} defined by (1) is given by

$$\Lambda_{\min}/\Lambda_{\max} = 1/(1 + q_\infty^2) \tag{6c}$$

Selection of the short-wave cutoff parameter q_∞ and the related wavelength Λ_{min} is the subject of this study.

The amplitude $A \equiv A(q, x)$ of the elementary wave E in the Fourier representation (4a) is commonly called wave-amplitude function, wave-spectrum function, or Kochin function. This function is defined in terms of a distribution of elementary plane waves over the mean wetted ship hull surface Σ. E.g., [19,1,23] show that the amplitude function A associated with an arbitrary distribution of sources, with density $\sigma(\boldsymbol{\xi})$, over Σ is given by

$$A \equiv \frac{1}{F^2}\int_\Sigma H(\xi - x)\,\sigma\,\mathcal{E}\,\mathrm{d}a \equiv A^{\mathrm{re}} + \mathrm{i}A^{\mathrm{im}} \tag{7a}$$

where $H(\cdot)$ is the usual Heaviside unit-step function, $\mathrm{d}a \equiv \mathrm{d}a(\boldsymbol{\xi})$ is the differential element of area at the point $\boldsymbol{\xi} \equiv (\xi, \eta, \zeta)$ of Σ, $\mathcal{E} \equiv \mathcal{E}(q, \boldsymbol{\xi})$ denotes the elementary wave function

$$\mathcal{E} \equiv \mathrm{e}^{(1+q^2)\zeta/F^2 - \mathrm{i}\sqrt{1+q^2}\,(\xi+q\eta)/F^2} \tag{7b}$$

and A^{re} and A^{im} are the real and imaginary parts of A. For the usual case, considered here, of a ship hull surface Σ that is symmetric about the ship centerplane $\eta = 0$, the amplitude function A defined by (7) is