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Hogner model of wave interferences for farfield ship waves in shallow water

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ABSTRACT

The remarkably simple yet realistic Hogner model of farfield ship waves, previously considered to analyze the apparent wake angle associated with the highest waves that result from constructive interferences among the divergent waves created by a fast ship in deep water, is applied to the more general case of uniform finite water depth. This theory is used to illustrate notable features of ship waves in finite water depth. In particular, numerical applications to a monohull ship and catamarans illustrate two notable features of ship waves in shallow water: specifically, the apparent wake angle can be much smaller than Havelock's classical asymptote or cusp angles, and the apparent wake angle in finite water depth is nearly identical to the apparent wake angle in deep water if the water depth is greater than the ship length. Moreover, the numerical illustrations demonstrate the paramount importance of interferences among divergent waves for fast ships. Indeed, constructive interferences among the divergent waves created by a fast ship largely determine the variation of the amplitude of the waves across the ship wake, and therefore the apparent wake angle and the wave drag of the ship, a critical element of ship design. These numerical illustrations also corroborate main conclusions of an approximate analysis of wave interferences in shallow water for monohull ships and catamarans modeled as 2-point wavemakers.

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1. Introduction

The farfield waves created by a monohull ship of length L, or a catamaran with identical twin hulls of length L separated by a lateral distance S, that travels at a constant speed V in calm water of uniform finite depth D and large horizontal extent are considered within the usual framework of linear potential flow theory. This classical theoretical framework is realistic, and the only practical option, to analyze farfield ship waves. The highest waves associated with constructive interferences among the divergent waves created by the ship hull (predominantly by the bow and the stern of the ship) at a high Froude number are of primary interest. The Froude number F is defined as

$$F \equiv \frac{V}{\sqrt{gL}} \tag{1}$$

where g denotes the gravitational acceleration. The nondimensional water depth

$$d \equiv \frac{Dg}{V^2} \tag{2}$$

is also defined. Finite water depth effects are only significant if $d < d_\infty \approx 3$ as is well known, and the water depth is then effectively infinite if $3 < d$.

The flow around the ship hull is modeled in accordance with the classical Hogner flow model [1], i.e. via a distribution of sources and sinks over the mean wetted hull surface Σ of the ship. The source density in Hogner's model is equal to the component n^x of the unit vector $\mathbf{n} \equiv (n^x, n^y, n^z)$ normal to the ship hull surface Σ, where $\mathbf{n}$ points into the water. This simple flow model explicitly defines the flow around a ship hull in terms of the Froude number and the ship hull geometry, and moreover defines farfield ship waves without computations of the nearfield flow around the ship hull.

Hogner's flow model has previously been used in [2–5] to analyze farfield waves created by fast ships in deep water. These studies of farfield ship waves in deep water show that, despite its remarkably simplicity, the Hogner model is realistic and useful. The Hogner theory of farfield ship waves in deep water is applied here to the more general case of water of uniform finite depth. Moreover, the

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analysis of the highest waves that result from constructive interferences among the divergent waves created by a fast ship considered in [2–5] for deep water is extended to shallow water of finite depth.

The analytical and numerical study of wave interference effects in shallow water, for monohull ships and catamarans modeled via Hogner's hull-surface distributions of sources and sinks, that is considered here also extends the analytical studies of interference effects in shallow water given in [6,7] for ships modeled as 2-point wavemakers. Specifically, a monohull ship is modeled as a point source at the ship bow and a point sink at the stern, i.e. as a source-sink pair, and a catamaran is modeled as two point sources at the twin bows of the catamaran, i.e. as a pair of point sources, in the elementary ship models previously considered in [6,7]. The analysis of interference effects for elementary 2-point ship models considered in [6,7] for uniform water depth is considerably more complex than the similar analysis of 2-point ship models considered in [8,11] for deep water, and shows that wave interferences are more complicated in shallow water than in deep water.

Thus, the numerical analysis of wave interference effects for farfield ship waves in shallow water considered here extends the analytical and numerical studies of wave interference effects already given in [2–7]. In particular, main conclusions of the analytical studies of basic 2-point ship models given in [6,7] are illustrated and corroborated by the more precise numerical analysis, based on the Hogner hull-surface source distribution flow model, that is considered here.

2. Hogner model of ship waves in shallow water

The waves created by the ship are observed from an orthogonal frame of reference and related coordinates (X, Y, Z) attached to the ship. The Z axis is vertical and points upward, and the undisturbed free surface is taken as the plane $Z=0$. The X axis is chosen along the path of the ship and points toward the ship bow. The nondimensional coordinates

$$\tilde{\mathbf{x}} \equiv (\tilde{x}, \tilde{y}, \tilde{z}) \equiv \frac{(\tilde{X}, \tilde{Y}, \tilde{Z})g}{V^2} \equiv \frac{\tilde{\mathbf{X}}g}{V^2} \tag{3a}$$

$$\mathbf{x} \equiv (x, y, z) \equiv \frac{(X, Y, Z)}{L} \equiv \frac{\mathbf{X}}{L} \tag{3b}$$

are used. Hereinafter, $\tilde{\mathbf{X}}$ and $\tilde{\mathbf{x}}$ denote a flow-field point located within the flow region outside the mean wetted ship hull surface Σ, and $\mathbf{X}$ and $\mathbf{x}$ denote a point of Σ. The coordinates of the flow-field point $\tilde{\mathbf{x}}$ are nondimensional in terms of the reference length V^2/g associated with the ship speed V, as is appropriate for a farfield analysis, whereas the coordinates of the hull-surface point $\mathbf{x}$ are nondimensional with respect to the ship length L.

The flow created by the ship, in water of uniform finite depth, is evaluated in accordance with the Hogner flow model [1], as in [2–4] for ship waves in deep water. Hogner's simple approximation is shown in [2] to predict wave patterns that can hardly be distinguished from the wave patterns obtained via the more precise Neumann–Michell theory given in [12,13].

Specifically, the Hogner approximation ϕ^H to the flow potential $\phi \equiv \Phi/(VL)$ at a flow-field point $\tilde{\mathbf{x}}$ is given by

$$\phi^H(\tilde{\mathbf{x}}) = \int_\Sigma G(\tilde{\mathbf{x}}, \mathbf{x}) n^x(\mathbf{x}) da(\mathbf{x}) \tag{4}$$

where $da(\mathbf{x}) \equiv dA/L^2$ denotes the differential element of area at a point $\mathbf{x}$ of the hull surface Σ, $n^x(\mathbf{x})$ is the x-component of the unit vector $\mathbf{n}$ normal to Σ at $\mathbf{x}$ as was already noted, and $G \equiv G(\tilde{\mathbf{x}}, \mathbf{x})$ represents the velocity potential of the flow created at a flow-field point $\tilde{\mathbf{x}}$ by a unit source at a point $\mathbf{x}$ and is the Green function associated with the classical linearized free-surface boundary condition. The Hogner approximation (4) explicitly defines the flow created by the ship in terms of the water depth, the Froude number, and the ship hull geometry.

The Green function G in (4) can be formally decomposed into a wave component W and a non-oscillatory local flow component, as is shown in, e.g. [14] for deep water. The local flow component L decays rapidly and is ignored in the analysis of farfield waves considered here. The wave component $W(\tilde{\mathbf{x}}, \mathbf{x})$ given in [14] for deep water becomes

$$W(\tilde{\mathbf{x}}, \mathbf{x}) = \frac{H(x - \tilde{x})}{\pi F^2} \mathrm{Im} \int_{k_0}^{k_\infty} \frac{\tilde{\mathcal{E}}_+ \mathcal{E}^+ + \tilde{\mathcal{E}}_- \mathcal{E}^-}{\sqrt{t(k - t)}} dk \tag{5}$$

for the more general case of finite water depth. Here, $H(\cdot)$ is the usual Heaviside unit-step function, F is the Froude number (1), Im means that the imaginary part is considered, and $k_0(d)$ is defined as

$$k_0(d) \equiv \left\{ \begin{array}{c} 0 \\ \text{root of } k = t \end{array} \right\} \quad \text{if} \quad \left\{ \begin{array}{c} d \le 1 \\ 1 < d \end{array} \right\} \tag{6}$$

where

$$t \equiv \tanh(kd) \tag{7}$$

Moreover, $\tilde{\mathcal{E}}_\pm \equiv \tilde{\mathcal{E}}_\pm(k, \tilde{\mathbf{x}})$ and $\mathcal{E}^\pm \equiv \mathcal{E}^\pm(k, \mathbf{x})$ denote the basic wave functions

$$\tilde{\mathcal{E}}_\pm \equiv \frac{\cosh[k(\tilde{z} + d)]}{\cosh(kd)} e^{\mathrm{i}(\alpha\tilde{x} \pm \beta\tilde{y})} \tag{8a}$$

$$\mathcal{E}^\pm \equiv \frac{\cosh[k(z/F^2 + d)]}{\cosh(kd)} e^{-\mathrm{i}(\alpha x \pm \beta y)/F^2} \tag{8b}$$

where

$$\alpha \equiv \sqrt{kt}, \quad \beta \equiv \sqrt{k(k - t)} \quad \text{and} \quad k_0 \le k \tag{9}$$

The wave functions (8a) represent elementary waves that propagate at angles $\gamma_\pm$ from the x-axis given by

$$(\cos\gamma_\pm, \sin\gamma_\pm) = \left(\sqrt{\frac{t}{k}}, \pm\sqrt{\frac{1 - t}{k}} \right) \tag{10}$$

The finite limit of integration k_∞ in (5) eliminates unrealistic short waves, notably waves influenced by surface tension and viscosity, that correspond to $k_\infty < k$.

Expressions (4) and (5) define the potential $\phi^W \equiv \Phi^W g/V^3$ associated with the waves aft of the ship as a superposition

$$\phi^W(\tilde{\mathbf{x}}) = \frac{1}{\pi} \mathrm{Im} \int_{k_0}^{k_\infty} \frac{A^+(k)\tilde{\mathcal{E}}_+(k, \tilde{\mathbf{x}}) + A^-(k)\tilde{\mathcal{E}}_-(k, \tilde{\mathbf{x}})}{\sqrt{t(k - t)}} dk \tag{11}$$

of elementary wave functions $\tilde{\mathcal{E}}_\pm(k, \tilde{\mathbf{x}})$ where the amplitude functions $A^\pm(k, F)$ are given by the distributions

$$A_1^\pm \equiv \frac{1}{F^4} \int_\Sigma n^x(\mathbf{x}) \mathcal{E}^\pm(k, \mathbf{x}) da(\mathbf{x}) \tag{12a}$$

of elementary wave functions $\mathcal{E}^\pm(k, \mathbf{x})$ over the ship hull surface Σ. Expression (12a) for a monohull ship becomes

$$A_2^\pm = 2\cos\left(\frac{\beta s}{2F^2}\right) A_1^\pm \tag{12b}$$

for a catamaran with identical twin hulls separated by a distance $s \equiv S/L$.

The free-surface elevation $e \equiv E\,g/V^2$ associated with the waves is $e(\tilde{x}, \tilde{y}) = \partial\phi^W(\tilde{x}, \tilde{y}, 0)/\partial\tilde{x}$. Expressions (11), (8a) and (9) then yield

$$e(\tilde{x}, \tilde{y}) = \frac{1}{\pi} \mathrm{Re} \int_{k_0}^{k_\infty} \frac{A^+(k) e^{\mathrm{i}h\varphi^+} + A^-(k) e^{\mathrm{i}h\varphi^-}}{\sqrt{1 - t/k}} dk \tag{13}$$

where $h\varphi^\pm \equiv \alpha\tilde{x} \pm \beta\tilde{y}$ and Re means that the real part is considered.

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