



Interference effects on the Kelvin wake of a catamaran represented via a hull-surface distribution of sources

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ABSTRACT

Wave-interference effects on the far-field waves created by a catamaran, with identical twin hulls of length L at a lateral separation distance S , that advances at constant speed V along a straight path in calm water of large depth are considered. Systematic computations are performed for 125 Froude numbers $F_s \equiv V/\sqrt{gS}$ (where g denotes the acceleration of gravity) within the range $0.4 \leq F_s \leq 3.5$, 25 hull spacings $s \equiv S/L$ within the range $0.2 \leq s \leq 0.8$, and seven simple mathematically-defined hulls that correspond to a broad range of main hull-shape parameters (beam/length, draft/length, beam/draft, waterline entrance angle), i.e. for 21,875 distinct cases in all. The two dominant wake angles ψ^i and ψ^o that correspond to the ray angles $\psi = \pm\psi^i$ and $\psi = \pm\psi^o$ where the largest divergent waves are found within the Kelvin wake $-\psi^K \leq \psi \leq \psi^K$ with $\psi^K \approx 19^\circ 28'$ are determined numerically via a realistic yet practical method. This practical method, used previously for monohull ships, is based on the numerical determination of the two major peaks of the amplitude function in the Fourier-Kochin representation of far-field ship waves, evaluated via the Hogner approximation and the stationary-phase approximation. The computations show that the hull shape only has a relatively small influence on the wake angles ψ^i and ψ^o associated with the dominant waves. A useful practical consequence of this numerical finding is that the two wake angles ψ^i and ψ^o can be estimated, without computations, for general catamarans in terms of the Froude number F_s and the hull spacing s via simple analytical approximations, obtained here via parametric computations. The computations also show that lateral interference effects are dominant if s and/or F_s are sufficiently large, i.e. for 'wide' and/or 'fast' catamarans. Moreover, the computations reported here for catamarans represented via hull-surface distributions of sources show that the basic two-point wavemaker model of interference between the waves created by the twin bows of a catamaran is realistic for wide and/or fast catamarans. However, wave-interference effects are more complicated if both s and F_s are small, i.e. for 'narrow slow' catamarans. The numerical analyses of dominant waves considered earlier for monohull ships and here for catamarans show that, although the amplitudes of the waves created by a ship are strongly influenced by the shape of the ship hull, the ray angles where the largest waves are found are mostly a kinematic feature that is only weakly influenced by the hull shape and the related wave amplitude.

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1. Introduction

It has long been observed, notably in [1–7], that the far-field waves created by a ship that steadily advances at high speed in calm water of large depth appear to be contained within a wedge $-\psi_{\max} \leq \psi \leq \psi_{\max}$ where the 'apparent wake angle' $\psi_{\max}$ can be significantly smaller than the cusp angle $\psi^K \approx 19^\circ 28'$ predicted by

Kelvin [8] via a classical asymptotic analysis based on a one-point wavemaker approximation of the flow created by a ship, linear potential flow theory, and the method of stationary phase. The one-point wavemaker model is a major simplification, and is the most restrictive assumption of Kelvin's analysis.

A number of studies have shown that several effects not considered by Kelvin can significantly affect the wake of a ship. In particular, the influence of nonlinearities, ambient waves, wind, shear current, surface tension, and water depth is considered in [4,6,9–13]. These studies show that 'extraneous' effects ignored by Kelvin can have a significant influence. However, most of the foregoing studies of ship wakes are not directly related to Kelvin's practical purpose of explaining the wave patterns created by

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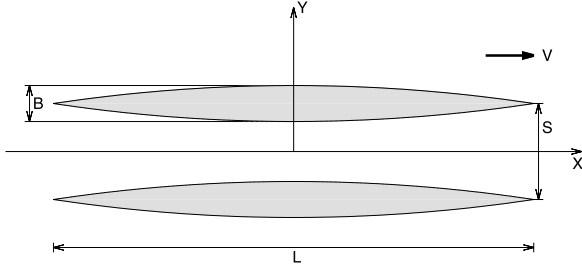


Fig. 1. Top view of a catamaran that consists of two identical demi-hulls, of length L and beam B , separated by a distance S , that advances in calm water at constant speed V along the x axis.

common ships that advance at constant speed in calm water of large depth, as noted in [14] where the recent literature related to the Kelvin wake of a ship is further considered. Indeed, the fact that effects not considered in Kelvin's classical analysis can significantly modify the Kelvin wake of a ship does not imply that the observations of narrow ship wakes reported in the literature are actually due to these extraneous effects. The foregoing studies in fact do not explain observed narrow ship wakes, notably because they do not improve Kelvin's fundamental model and most restrictive simplification of a ship as a one-point wavemaker.

Numerical computations, within the context of linear potential flow theory, of the far-field waves created by Gaussian distributions of pressure at the free surface [15–18] or distributions of sources over ship hull surfaces [14,19] show that, at high Froude numbers, the largest waves created by surface-distributions of pressure or sources are found along ray angles $\psi = \pm\psi_{\max}$ that are located inside the cusp lines $\psi = \pm\psi^k$ of the classical Kelvin wake. This numerical finding is consistent with the elementary analysis of constructive and destructive interference between the waves created by a two-point wavemaker – specifically, a point source and a point sink located at the bow and the stern of a monohull ship, or two point sources (or sinks) located at the bows (or sterns) of the twin hulls of a catamaran – considered in [20,21] for deep water and in [22,23] for uniform finite water depth.

Thus, the computations of waves due to surface distributions of pressure or sources reported in [14–19] as well as the analysis of interference effects for a two-point wavemaker (an elementary approximation to a distribution of sources over a ship hull surface by means of a point source and a point sink for a monohull ship, or two point sources for a catamaran) given in [20–23] suggest that the observations of narrow ship wakes reported in the literature most likely correspond to the rays $\psi = \pm\psi_{\max}$ where the largest waves created by a high-speed ship are found. More precisely, [20–23,14] contend that narrow ship wakes observed for high-speed ships are merely the unsurprising consequence of longitudinal interference between the divergent waves created by sources and sinks distributed over the bow and stern regions of a ship hull surface, and lateral interference between the divergent waves created by sources (or sinks) distributed over the port and starboard sides of a hull surface or the twin hulls of a catamaran. Wave interference (a main feature of the linear potential flow theory of ship waves) is then a very simple, indeed nearly trivial, explanation of the observation of narrow Kelvin ship wakes reported in the literature.

The far-field waves created by a monohull ship, represented via a distribution of sources over the ship hull surface, are considered in [14] where a practical method is used to numerically determine the apparent wake angle $\psi_{\max}$ for seven ship hulls that correspond to broad ranges of main hull-shape parameters (beam/length, draft/length, beam/draft, waterline entrance angle) at ten Froude numbers F within the range $0.6 < F \leq 1.5$. The systematic numerical computations considered in [14] show that the apparent

wake angle $\psi_{\max}$ is only weakly influenced by the shape of the ship hull. A useful practical consequence of this numerical finding is that the wake angle $\psi_{\max}$ can be estimated for general monohull ships (of arbitrary hull shape) via simple analytical relations, obtained in [14] from parametric computations. These analytical relations provide useful practical estimates, without computations, of the apparent wake angle $\psi_{\max}(F)$ for arbitrary ship hull forms and Froude numbers. The numerical study of wave-interference effects considered in [14] for monohull ships is extended here to catamarans, a more interesting and significantly more complicated case as shown further on.

Thus, the far-field waves created by a catamaran that advances at constant speed V along a straight path in calm water of large depth and lateral extent are considered here. The catamaran consists of two identical demi-hulls of length L , beam B and draft D , separated by a distance S , as depicted in Fig. 1. The nondimensional separation distance s between the twin hulls of the catamaran, called hull spacing hereafter, is defined as

$$s \equiv S/L. \quad (1)$$

The Froude numbers F_s and F based on the separation distance S between the twin hulls of the catamaran or the length L of the hulls are

$$F_s \equiv V/\sqrt{gS} \equiv F/\sqrt{s} \quad (2a)$$

$$F \equiv V/\sqrt{gL} \equiv F_s\sqrt{s} \quad (2b)$$

where g denotes the gravitational acceleration. The waves created by the catamaran are observed from a Galilean frame of reference attached to the moving 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, half way between the twin hulls of the catamaran, and points toward the ship bow. The demi-hulls are symmetric about the centerplanes $Y = \pm S/2$. Nondimensional coordinates

$$(x, y, z) \equiv (X, Y, Z)/L \quad (3)$$

are defined.

Systematic computations are performed for 125 Froude numbers F_s within the range $0.4 \leq F_s \leq 3.5$, 25 hull spacings s within the range $0.2 \leq s \leq 0.8$, and seven simple (mathematically-defined) hulls that correspond to broad ranges of main hull-shape parameters (beam/length, draft/length, beam/draft, waterline entrance angle), i.e. for 21,875 distinct cases in all. The hulls of the catamaran are defined as

$$\pm y = \frac{s}{2} \pm \frac{b}{2} [1 - (2x)^{2n}] \left(1 - \frac{z^2}{d^2}\right) \quad (4)$$

where the beam/length ratio $b \equiv B/L$, the draft/length ratio $d \equiv D/L$ and the waterline-shape coefficient n for the seven hulls considered in the computations are chosen as listed in Table 1. The corresponding waterline entrance angle 2α and names that identify the hulls are also noted in Table 1. The seven hulls considered in the computations correspond to the relatively broad ranges of main hull-shape parameters

$$0.05 \leq \frac{B}{L} \leq 0.1, \quad 0.0375 \leq \frac{D}{L} \leq 0.075$$

$$1 \leq \frac{B}{D} \leq 2, \quad 17.1^\circ \leq 2\alpha \leq 48.5^\circ.$$

The dominant wake angles that correspond to the largest divergent waves are determined here via the practical numerical method used in [14]. Briefly, the dominant wake angles are determined numerically from the peaks of the wave-amplitude function in the Fourier-Kochin representation of far-field ship

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