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Viscosity and nonlinearity effects on the forces and waves generated by a floating twin hull under heave oscillation

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ABSTRACT

Nonlinear hydrodynamics of a twin rectangular hull under heave oscillation is analyzed using numerical methods. Two-dimensional nonlinear time-domain solutions to both inviscid and viscous problems are obtained and the results are compared with linear, inviscid frequency-domain results obtained in [26] to quantify nonlinear and viscous effects. Finite-difference methods based on boundary-fitted coordinates are used for solving the governing equations in the time domain [2]. A primitive-variables based projection method [6] is used for the viscous analysis and a mixed Eulerian–Lagrangian formulation [11] for inviscid analysis. The algorithms are validated and the order of accuracy determined by comparing the results obtained from the present algorithm with the experimental results of Vugt [22] for a heaving rectangle in the free surface. The present study on the twin-hull hydrodynamics shows that at large and non-resonant regular frequencies, and small amplitude of body oscillation, the fluid viscosity does not significantly affect the wave motion and the radiation forces. At low frequencies however the viscosity effect is found to be significant even for small amplitude of body oscillation. In particular, the hydrodynamic force obtained from the nonlinear viscous analysis is found to be closer to the linear inviscid force than the nonlinear inviscid force to the linear inviscid force, the reason for which is attributed to the wave dampening effect of viscosity. Since the wave lengths generated at smaller frequencies of oscillation are longer and therefore the waves could have a more significant effect on the dynamic pressure on the bottom of the hulls which contribute to the heave force, the correlation between the heave force and the wave elevation is found to be larger at smaller frequencies. Because of nonlinearity, the wave radiation and wave damping force remained nonzero even at and around the resonant frequencies – with the resonant frequencies as determined in [26] using linear potential flow theory. As to be expected, the nonlinear effect on the wave force is found to be significant at all frequencies for large amplitude of oscillation compared to the hull draft. The effect of viscosity on the force, by flow separation, is also found to be significant for large amplitude of body oscillation.

1. Introduction

Both for practical and theoretical reasons, researchers have extensively studied the dynamics and hydrodynamics of multihull bodies in a free surface. The possibility of achieving efficient sea-keeping and wave-resistance characteristics, in addition to large deck area, has driven the interest of naval architects toward the subject [27]. Examination of the force and wave characteristics at the natural wave frequencies associated with multihulls has been the focus of several theoretical studies as in McIver and McIver [14], McIver [13], Newman [17], Wang and Wahab [23], Porter and Evans [18], Yeung and Seah [26] and Mavrakos [12]. These studies have uncovered several fascinating wave phenomena occurring in the presence of multi-hull bodies in a free surface. For instance, certain multi-hull shapes can have non-radiating (trapped) waves as solutions to the linear frequency-domain problem which in turn affects the uniqueness and existence of solutions to linear wave–body interaction problems. The trapped mode corresponds to non-trivial solution to the linear homogeneous inviscid frequency-domain problem governing certain multihull or concentric annular geometries [26]. At the trapped wave frequencies, solutions to the frequency-domain radiation and diffraction problems do not exist or be unique. In other words, as explained in [21,26], for the body oscillating at a regular frequency the far-field radiating wave will be at frequency of body oscillation while the near field wave will be waves of both the forcing and trapped-mode frequencies; for the body oscillating at the trapped-mode frequency the solution becomes infinity in the near field.

Studies have shown that hydrodynamic characteristics of a multihull is vastly different from that of a single hull with variation

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A	amplitude of hull oscillation
B	beam of each demi-hull
b	half beam of the demi hull = $B/2$
d	mean draft of the twin-hull
F	hydrodynamic heave force on the hull
$\mathcal{F}$	free surface boundary
Fn	$\sigma\sqrt{b/g}$ = Froude number; and frequency parameter
$\mathcal{H}$	Hull boundary
p	total pressure
Re	$g^{1/2}B^{3/2}/\nu$ = a Reynolds number defined in terms of B and g.
$\vec{t}$	stress vector = $\tilde{\sigma}\cdot\hat{n}$
S	inner separation distance between the demi hulls
T	period of heave oscillation
$\vec{t}$	stress vector
$\vec{u}$	(u, v, w) = flow velocity field
w	total beam of the twin hull = $S+2B$
$\vec{X}_f = (X_f, Y_f, Z_f)$	coordinates of a free-surface particle
Y_h	heave displacement of the hull
$Y = Y(x, t)$	Free-surface elevation
μ	coefficient of viscosity; added-mass coefficient
ν	coefficient of kinematic viscosity μ/ρ; frequency parameter σ^2/g
ρ	fluid density
σ	frequency of heave oscillation
Σ	far-field open boundary
τ	time in the computational space
$\tilde{\sigma} = \sigma_{ij}$	Stress tensor of the fluid

of radiation hydrodynamic coefficients of a multihull with respect to frequency showing multiple spikes corresponding to resonant wave motions. The natural wave modes associated with the multihulls include the vertical oscillation of the mean surface, known as the Helmholtz or piston wave mode, and the sloshing standing wave modes between the two rigid bodies in a free surface [16]. Inviscid analysis have shown that around the critical frequencies corresponding to the Helmholtz and sloshing-mode wave resonances, the wave damping force becomes zero and the added-mass coefficients undergo large variations with respect to frequency of oscillation [26].

Most analyses and findings on multi-hull hydrodynamics were based on solutions to the linear inviscid problem and in the frequency domain. The linear time-domain analysis of the inviscid problem by McIver et al. [15] was able to capture the trapped waves for certain multi-hull geometries as earlier predicted by their theory [14].

Studies focused on the effects of free-surface nonlinearity and fluid viscosity on the radiation hydrodynamics of multiple hulls have been few and also quite recent. The two-dimensional viscous flow analysis, as well as experimental studies, carried out by Faltinsen et al. [8] and then by Kristiansen and Faltinsen [9] point to the significance of free-surface nonlinearity and viscosity in the wave motions between multiple hulls and moonpools at large amplitude of body and wave motions. The present work is complementary to above studies in that it examines the significance of the effect of viscosity, for e.g., from flow separation and wave damping, and free-surface nonlinearity resulting from large-amplitude motions, on the wave radiation and radiation forces of multihull bodies. The present study, which is numerical, is carried out to determine the nonlinear and viscous effects in radiation hydrodynamics of multihull bodies. For quantification of the effects by comparison, we consider here the linear inviscid results obtained for the same problem in Yeung and Seah [26].

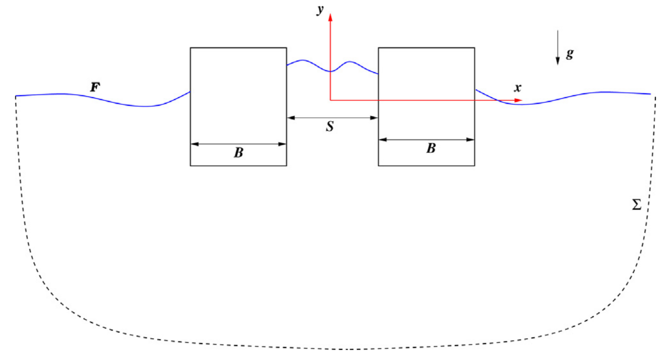

Fig. 1. Illustration of heave oscillation of a twin rectangular hull in a free surface.

For analysis, a finite-difference method based on curvilinear coordinates, developed in [1,2,28], has been used. The solution method has been used to solve a range of free-surface flow problems involving wave–body and wave–vortex interactions as in [1–3]. The method and algorithms have thus been thoroughly vetted and validated. In this paper, the method is validated and its accuracy determined through comparison of numerical results with experimental results given in [22] for a closely related problem of heave motion of a floating rectangle.

Representative results and preliminary findings of the present work were presented by the author at the 2012 OMAE Symposium honoring Professor Ronald W. Yeung [4].

2. Equations governing the inviscid-flow problem

As illustrated in Fig. 1, we consider a twin rigid rectangular hull under heave oscillation. As summarized in the notations section of the paper (at the beginning), the beam of each demi hull is denoted as B, the total beam as w, half-beam of demi hull as $b = B/2$, the inner separation distance between the demi hulls as S (= $w - 2B$) and the mean draft as d. The fluid density is denoted as ρ, coefficient of viscosity as μ and the acceleration of gravity as g. The amplitude and frequency of heave oscillation are denoted as A and σ, respectively. The boundaries of the problem domain are the wetted-surface hull boundary $\mathcal{H} \equiv \mathcal{H}(t)$, free surface $\mathcal{F} \equiv \mathcal{F}(t)$ and a fixed open-boundary Σ in the far field.

In the case of an inviscid, incompressible and irrotational flow, the basic equation to be solved is the Laplace equation for the velocity potential ϕ:

$$\nabla^2\phi = 0 \quad (1)$$

with velocity field $\vec{u} = \nabla\phi$. The appropriate form of the Euler's integral to consider in the numerical analysis of fully nonlinear inviscid flow problem is given by

$$p = -\rho\left[\frac{\partial\phi}{\partial\tau} - \frac{\partial x}{\partial\tau}\frac{\partial\phi}{\partial x} - \frac{\partial y}{\partial\tau}\frac{\partial\phi}{\partial y}\right] - \frac{\rho}{2}|\nabla\phi|^2 - \rho g y \quad (2)$$

where $\partial/\partial\tau$ here denotes variation with respect to time in appropriate spatial frame In the special case in which the spatial nodes are fixed, i.e.,

$$\frac{\partial x}{\partial\tau} = 0, \quad \frac{\partial y}{\partial\tau} = 0, \quad \rightarrow \frac{\partial\phi}{\partial\tau} = \frac{\partial\phi}{\partial t}$$

the above equation reduces to the familiar *Eulerian form* of the Euler's integral:

$$p = -\rho\frac{\partial\phi}{\partial t} - \frac{\rho}{2}|\nabla\phi|^2 - \rho g y \quad (3)$$