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Nonlinear loading of a two-dimensional heaving box

Marcos Rodriguez, Johannes Spinneken*, Chris Swan

Imperial College London, Department of Civil and Environmental Engineering, London SW7 2AZ, UK

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ABSTRACT

A numerical investigation is presented addressing the nonlinear heave response of a rectangular box. The work specifically concerns the importance of the relative body dimensions, expressed through the product of the half-beam b and the wavenumber k. When subjected to moderately steep incident waves, the second-harmonic content of the heave motion is found to be as large as 25% of the first-harmonic content. In considering the extent of this second-harmonic motion, three regimes may be defined: (i) the long wave regime, where $kb \leq 0.4$, (ii) the intermediate regime, where $0.4 < kb < 1.0$ and (iii) the diffraction or short wave regime, where $kb \geq 1.0$. Expressed in terms of the wavelength $\lambda = 2\pi/k$, these regimes correspond to (i) $b \leq 0.06\lambda$, (ii) $0.06\lambda < b < 0.16\lambda$ and (iii) $b \geq 0.16\lambda$. The second-harmonic motion content is found to be particularly pronounced in regimes (i) and (iii). Perhaps surprisingly, this second-harmonic content is also found to be practically non-existent for some intermediate cases lying within regime (ii). Three sources of nonlinearity are shown to be particularly important. First, the interaction between the first-order incident waves and the first-order scattered waves is key to the nonlinear loading in regime (iii). Second, the generation of freely propagating second-harmonic radiated waves due to the body motion is important in (i). Third, the local standing wave field associated with the radiation problem is found to contribute to the loading in regime (iii). In addition, the location of the body resonance also plays a critical role in defining the extent of the second-harmonic motion content. The focus of the present work lies on a clear physical interpretation of the sources of these nonlinear loads, coupled with an analysis of the body dynamics.

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1. Introduction

1.1. The nonlinear radiation–diffraction problem

In many practical applications, the floating body problem is separated into two linearly independent problems: (A) the excitation problem and (B) the radiation problem. Within the excitation problem, the structure is considered fixed in position and the so-called excitation forces are determined. In contrast, the radiation problem concerns the forced motion of a body and its hydrodynamic properties based on the radiated wave field. Adopting linear superposition, (A) and (B) are combined to model the freely floating response of a structure.

There are many load cases where a linear hydrodynamic analysis is inadequate. Common examples include a body being driven by steep incident waves or one undergoing large body excursions. Any nonlinear interactions that arise in either the incident wave

* Corresponding author.
E-mail address: j.spinneken@imperial.ac.uk (J. Spinneken).

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field or the body's (motion) response prohibit the use of linear superposition. These nonlinear interactions lead to considerably more challenging formulations, which are difficult to solve analytically (or semi-analytically) beyond second order.

Significant effort has been made to develop radiation–diffraction solutions valid to second order. The main difficulty in obtaining such solutions lies in satisfying the inhomogeneous second-order free surface boundary condition. To overcome this difficulty, both Molin (1979) and Lighthill (1979) adopted an indirect approach in which the second-order diffraction forces are evaluated without explicitly calculating the second-order potential. Solutions of this type rely on the evaluation of a free surface integral. In this context, Eatock Taylor and Hung (1987) and Molin and Marion (1985) developed solutions to efficiently calculate this integral by making assumptions about the behaviour of the second-order potential at large distances from the body.

Kim and Yue (1989, 1990) extended this earlier work, achieving a full and direct solution of the velocity potential for both monochromatic and bichromatic waves. A 'partially nonlinear' approach, which addresses linear (small amplitude) incident waves but considers diffraction effects up to second order, was presented by Sulisz (1993). Within this solution a method of matched eigenfunction expansions is used to solve the Boundary Value Problem (BVP) for a fixed rectangular body. This produces a complete expression for the velocity potential in two dimensions.

All of the solutions noted above were formulated in the frequency domain. Alongside this work advances in computational resources have enabled the development of fully nonlinear time-domain solvers, commonly relying on a Boundary Element Method (BEM). Nonlinear BEM formulations have been shown to efficiently model a wide variety of scenarios related to wave generation and evolution, as demonstrated by Longuet-Higgins and Cokelet (1976), Grilli and Horrillo (1997), Hague and Swan (2009), Christou et al. (2009) and Spinneken et al. (2014). In addition to capturing the full extent of the nonlinear interactions, fully nonlinear descriptions also offer benefits in terms of implementation and convergence. These types of approaches avoid the need for any special treatment of the slowly converging free surface integrals commonly reported in second-order formulations. Indeed, despite appearing to be more challenging due to their nonlinear formulation, the implementation and convergence of fully nonlinear time-domain solutions can often be less challenging than that of second-order formulations. The only drawback of applying a fully nonlinear solution lies in the computational effort associated with the time marching. However, in a two-dimensional context, the relatively low number of computational nodes ensures that this is not a barrier to its effective implementation.

Other examples of nonlinear diffraction methods include the work by Ma et al. (2001), in which a finite element method was used to compute the three-dimensional interaction between steep incident waves and fixed bodies. Results were presented for the nonlinear diffraction around a vertical cylinder incorporating both monochromatic and bichromatic incident waves. Xue et al. (2001) used a mixed Eulerian–Lagrangian high-order boundary element method to investigate nonlinear diffraction scenarios in three dimensions. This includes the generation of bow waves from ships and the 'ringing' loads on a surface-piercing vertical cylinder in steep regular waves. Ferrant et al. (2003) provided a related investigation, again undertaken in the time domain, in which a BEM implementation of the initial boundary-value problem was used to investigate the nonlinear diffraction by arbitrary 3D structures. In the context of the nonlinear radiation problem, notable contributions include Maiti and Sen (2001), Bai and Eatock Taylor (2006) and Zhou et al. (2013).

1.2. Nonlinearities in the floating body problem

Building upon the available body of work, the present study seeks to advance the understanding of the coupled floating-body problem. Specifically, the work aims to:

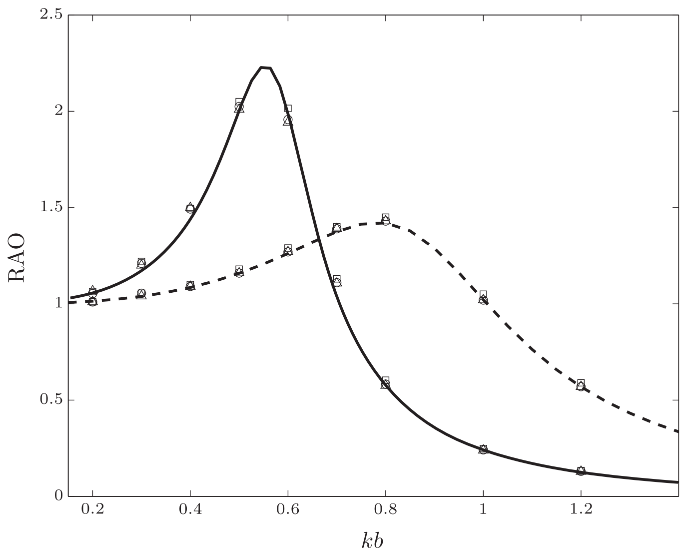

Fig. 1. Heave Response Amplitude Operator (RAO) for a rectangular box subjected to regular waves with $A_i k$=(a) △ 0.01, (b) ○ 0.05, (c) □ 0.10 (present nonlinear computations) and – – Linear RAO RB1,— Linear RAO RB2, where the geometries of cases RB1 and RB2 are as outlined in Table 1.

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