

Fifth-order nonlinear spectral model for surface gravity waves: From pseudo-spectral to spectral formulations

Wooyoung Choi

Department of Mathematical Sciences
New Jersey Institute of Technology
Newark, NJ 07102-1982, USA

Abstract

We present a fifth-order nonlinear spectral model describing the spectral evolution of nonlinear surface gravity waves in water of finite depth. Using the equivalence between pseudo-spectral and spectral formulations, it is shown that the spectral model can be easily obtained using a truncated Hamiltonian from the pseudo-spectral formulation. The fifth-order model is written explicitly in terms of two canonical variables (the Fourier transforms of the surface elevation and the free surface velocity potential) and preserves the Hamiltonian structure of the original water wave problem. Under discrete approximation, the time-periodic solutions of the spectral model for progressive and standing waves are shown to be consistent with the classical solutions of Stokes and Rayleigh, respectively, when truncated at the third order.

1 Introduction

For three-dimensional water waves, the free surface boundary conditions can be written (Zakharov 1967), in terms of the surface elevation $\zeta(\mathbf{x}, t)$ and the free surface velocity potential $\Phi(\mathbf{x}, t)$, as

$$\frac{\partial \zeta}{\partial t} + \nabla \Phi \cdot \nabla \zeta = \left(1 + |\nabla \zeta|^2\right) W, \quad \frac{\partial \Phi}{\partial t} + \frac{1}{2} |\nabla \Phi|^2 + g\zeta = \frac{1}{2} \left(1 + |\nabla \zeta|^2\right) W^2, \quad (1.1)$$

where \mathbf{x} is the the horizontal coordinate, t is time, ∇ is the horizontal gradient, and g is the gravitational acceleration. In (1.1), $\Phi(\mathbf{x}, t) \equiv \phi(\mathbf{x}, z = \zeta, t)$ and $W \equiv \partial \phi / \partial z(\mathbf{x}, z = \zeta, t)$ are the velocity potential and the vertical velocity evaluated at the free surface, respectively, where ϕ and z are the three-dimensional velocity potential and the vertical coordinate, respectively. The two equations in (1.1) can be regarded as a system of nonlinear evolution equations for ζ and Φ once W is expressed in terms of ζ and Φ . Depending upon how to close this system, various theoretical models have been developed.

A theoretical model particularly useful for numerical computations of the evolution of broadband nonlinear surface waves was proposed by West *et al.* (1987), who wrote W in

RIMS Workshop on Nonlinear Water Waves, May 22-26, 2018: In honor of Professor Mitsuhiro Tanaka on the occasion of his retirement

an infinite series that depend on ζ and Φ . By substituting the infinite series into (1.1), a closed system of nonlinear evolution equations for ζ and Φ was obtained. After assuming the wave steepness is small, the series can be truncated at a desired order of nonlinearity and the resulting system has been studied numerically using a pseudo-spectral method by numerous researchers, including, for example, Tanaka (2001*a, b*), Bateman *et al.* (2001), Choi *et al.* (2005), and Goulet & Choi (2011). Similar approaches have been proposed by Dommermuth & Yue (1987), Criag & Sulem (1993), and Clamond & Grue (2001).

An alternative approach to describe the evolution of broadband nonlinear waves was proposed by Zakharov (1968), who obtained a nonlinear integro-differential equation in spectral space for a single complex amplitude, which is a linear combination of the Fourier transforms of ζ and Φ . As a number of multiple integrals are required to be evaluated, the evolution equation of Zakharov is less efficient for numerical computations than the pseudo-spectral model of West *et al.* (1987). Nevertheless, his evolution equation is so useful for further analysis to describe the time evolution of wave spectra. For example, in his seminal work, Zakharov (1968) reduced the third-order equation to a relatively simpler form for resonant four-wave interactions. This equation is also often referred to as the (reduced) Zakharov equation, which has been studied numerically (Annenkov & Shriar 2001). The spectral models of Zakharov (1968) have been further extended to the fourth order by Stiassnie & Shemer (1984) to describe the five-wave interactions of gravity waves. Later the spectral models were reformulated by Krasitskii (1994) directly from a Hamiltonian approach along with canonical transformations to simplify the Hamiltonian. For the earlier development of the spectral formulation, see, for example, Yuen & Lake (1982) and Mei *et al.* (2005).

As one can imagine, the formulation of Zakharov (1968) should be equivalent to that of West *et al.* (1987). Therefore, it is expected to be straightforward to recover one formulation from the other. This is particularly useful if one is interested in a spectral model valid at a high order as the pseudo-spectral model of West *et al.* (1987) can be found conveniently at any order of nonlinearity through recursion formulas. Here it is shown that a fifth-order spectral model can be indeed obtained in a straightforward manner from the pseudo-spectral model of West *et al.* (1987) by taking advantage of its Hamiltonian structure.

2 Pseudo-spectral formulation

2.1 Expansion

By expanding W in Taylor series about $z = 0$, it was shown by West *et al.* (1987) that the expression for W can be written in infinite series as

$$W = \sum_{n=1}^{\infty} W_n, \quad W_n = \sum_{j=0}^{n-1} C_j[\Phi_{n-j}] \quad \text{for } n \geq 1, \quad (2.1)$$

where Φ_n are given by

$$\Phi_1 = \Phi, \quad \Phi_n = \sum_{j=1}^{n-1} \mathcal{A}_j[\Phi_{n-j}] \quad \text{for } n \geq 2, \quad (2.2)$$

and operators \mathcal{A}_n and \mathcal{C}_n are defined, with $\Delta = \nabla^2$, by

$$\mathcal{A}_{2m} = (-1)^{m+1} \frac{\zeta^{2m}}{(2m)!} \Delta^m, \quad \mathcal{A}_{2m+1} = (-1)^m \frac{\zeta^{2m+1}}{(2m+1)!} \Delta^m \mathcal{L}, \quad (2.3)$$

$$\mathcal{C}_{2m} = (-1)^{m+1} \frac{\zeta^{2m}}{(2m)!} \Delta^m \mathcal{L}, \quad \mathcal{C}_{2m+1} = (-1)^{m+1} \frac{\zeta^{2m+1}}{(2m+1)!} \Delta^{m+1}. \quad (2.4)$$

The linear operator $\mathcal{L}[f]$ is given by $\mathcal{L}[f] = \mathcal{F}^{-1}[-k \tanh(kh) \mathcal{F}[f]]$, where h is the water depth, and \mathcal{F} and \mathcal{F}^{-1} represent the Fourier transform and its inverse, respectively. Alternatively, the linear operator \mathcal{L} can be written as $\mathcal{L}[f] = \int K(\mathbf{x} - \boldsymbol{\xi}) f(\boldsymbol{\xi}) d\boldsymbol{\xi}$, where the kernel $K(\mathbf{x})$ is defined in Fourier space as $\mathcal{F}[K(\mathbf{x})] = -k \tanh(kh)$.

Although the expansion for W given by (2.1) requires no formal introduction of a small parameter, except for the existence of Taylor series, the series given by (2.1)–(2.2) can be considered as an expansion in terms of (small) wave steepness, in particular, when the infinite series need to be truncated for numerical simulations or further approximations. From $\zeta \nabla = O(\epsilon)$ and $\zeta \mathcal{L} = O(\epsilon)$, where $\epsilon = a/\lambda$ with a and λ being the characteristic wave amplitude and wavelength, respectively, one can see that $\Phi_n = O(\epsilon^n)$ and $W_n = O(\epsilon^n)$. Therefore, the rate of convergence is expected to improve as ϵ decreases.

2.2 System of West *et al.* (1987)

By substituting into (1.1) the expansion for W given by (2.1), the evolution equations for ζ and Φ are given by

$$\frac{\partial \zeta}{\partial t} = \sum_{n=1}^{\infty} Q_n(\zeta, \Phi), \quad \frac{\partial \Phi}{\partial t} = \sum_{n=1}^{\infty} R_n(\zeta, \Phi), \quad (2.5)$$

where Q_n and R_n are given by

$$Q_1 = W_1, \quad Q_2 = W_2 - \nabla \Phi \cdot \nabla \zeta, \quad Q_n = W_n + |\nabla \zeta|^2 W_{n-2} \quad \text{for } n \geq 3, \quad (2.6)$$

$$\begin{aligned} R_1 &= -g\zeta, \quad R_2 = -\frac{1}{2} |\nabla \Phi|^2 + \frac{1}{2} W_1^2, \quad R_3 = W_1 W_2, \\ R_n &= \frac{1}{2} \sum_{j=0}^{n-2} W_{n-j-1} W_{j+1} + \frac{1}{2} |\nabla \zeta|^2 \sum_{j=0}^{n-4} W_{n-j-3} W_{j+1} \quad \text{for } n \geq 4. \end{aligned} \quad (2.7)$$

Here the expressions of W_n are given by (2.1). Notice that $Q_n = O(\epsilon^n)$ are linear in Φ while $R_n = O(\epsilon^n)$ are quadratic in Φ .

For small amplitude waves, the system (2.5) can be linearized, with $W_1 = -\mathcal{L}[\Phi]$, to

$$\frac{\partial \zeta}{\partial t} = -\mathcal{L}[\Phi], \quad \frac{\partial \Phi}{\partial t} = -g\zeta, \quad (2.8)$$

which can be combined into $\partial^2 \zeta / \partial t^2 = g \mathcal{L}[\zeta]$. The same equation also holds for Φ . Substituting $(\zeta, \Phi) \sim \exp[i(\mathbf{k} \cdot \mathbf{x} - \omega t)]$ into (2.8) yields the linear dispersion relation given by

$$\omega^2 = g k \tanh kh, \quad (2.9)$$

where we have used $\mathcal{L} \left[e^{i\mathbf{k}\cdot\mathbf{x}} \right] = -k \tanh kh e^{i\mathbf{k}\cdot\mathbf{x}}$. While the leading-order terms (Q_1 and R_1) represent linear dispersive effects, Q_n and R_n for $n \geq 2$ describe nonlinear dispersive effects and nonlinear wave interactions.

Following West *et al.* (1987), the system given by (2.5) has been studied extensively in recent years using a pseudo-spectral method based on Fast Fourier Transform (FFT), for example, by Tanaka (2001*a, b*) and many others. For numerical computations, after assuming ζ and Φ are doubly periodic in space so that they can be written in Fourier series, the linear operators Δ and \mathcal{L} in (2.3)–(2.4) are evaluated in Fourier space:

$$\Delta = -k_{\mathbf{j}}^2, \quad \mathcal{L} = -k_{\mathbf{j}} T_{\mathbf{j}}, \quad (2.10)$$

where $\mathbf{j} = (j, l)$, $\mathbf{k}_{\mathbf{j}} = (jK_x, lK_y)$, $k_{\mathbf{j}} = |\mathbf{k}_{\mathbf{j}}|$, $T_{\mathbf{j}} = \tanh(k_{\mathbf{j}}h)$, and with K_x and K_y being the fundamental wavenumbers in the x and y directions, respectively. Then the two nonlinear operators \mathcal{A}_n and \mathcal{C}_n defined by (2.3) and (2.4) are computed as

$$\mathcal{A}_{2m} = -\frac{\zeta^{2m}}{(2m)!} k_{\mathbf{j}}^{2m}, \quad \mathcal{A}_{2m+1} = -\frac{\zeta^{2m+1}}{(2m+1)!} k_{\mathbf{j}}^{2m+1} T_{\mathbf{j}}, \quad (2.11)$$

$$\mathcal{C}_{2m} = \frac{\zeta^{2m}}{(2m)!} k_{\mathbf{j}}^{2m+1} T_{\mathbf{j}}, \quad \mathcal{C}_{2m+1} = \frac{\zeta^{2m+1}}{(2m+1)!} k_{\mathbf{j}}^{2m+2}. \quad (2.12)$$

In (2.11), to compute $\mathcal{A}_{2m}[f]$, the Fourier transform of f is multiplied by $-k_{\mathbf{j}}^{2m}/(2m)!$ in Fourier space and, then, its inverse Fourier transform is multiplied by ζ^{2m} in physical space. Finally, after evaluating its right-hand sides up to a desired order of nonlinearity, the system given by (2.5) is integrated in time.

2.3 Hamiltonians

Zakharov (1968) showed that the total energy defined by

$$E = \frac{1}{2} \int \left(g\zeta^2 + \Phi \frac{\partial \zeta}{\partial t} \right) d\mathbf{x}, \quad (2.13)$$

is the Hamiltonian for the water wave problem so that the evolution equations for ζ and Φ can be written as

$$\frac{\partial \zeta}{\partial t} = \frac{\delta E}{\delta \Phi}, \quad \frac{\partial \Phi}{\partial t} = -\frac{\delta E}{\delta \zeta}, \quad (2.14)$$

where $\delta E/\delta \zeta$ and $\delta E/\delta \Phi$ represent the functional derivatives of E with respect to the two conjugate variables ζ and Φ , respectively. Therefore, the total energy E is conserved. From (2.5), the total energy E defined in (2.13) can be expanded, in infinite series, as

$$E = \frac{1}{2} \int \left(g\zeta^2 + \Phi \sum_{n=1}^{\infty} Q_n \right) d\mathbf{x} = \sum_{n=2}^{\infty} E_n, \quad (2.15)$$

where Q_n are given by (2.7) and the n -th order energy E_n is given by

$$E_2 = \frac{1}{2} \int \left(g\zeta^2 + \Phi Q_1 \right) d\mathbf{x}, \quad E_n = \frac{1}{2} \int \Phi Q_{n-1} d\mathbf{x} \quad \text{for } n \geq 3. \quad (2.16)$$

2.4 Fifth-order model

When truncated at $O(\epsilon^5)$, the fifth-order nonlinear evolution equations for ζ and Φ can be obtained as

$$\frac{\partial \zeta}{\partial t} = \sum_{n=1}^5 Q_n(\zeta, \Phi), \quad \frac{\partial \Phi}{\partial t} = \sum_{n=1}^5 R_n(\zeta, \Phi), \quad (2.17)$$

where Q_n and R_n are given, explicitly, by

$$Q_1 = -\mathcal{L}[\Phi], \quad (2.18)$$

$$Q_2 = -\nabla \cdot (\zeta \nabla \Phi) - \mathcal{L}[\zeta \mathcal{L}[\Phi]], \quad (2.19)$$

$$Q_3 = -\mathcal{L}[\zeta \mathcal{L}[\zeta \mathcal{L}[\Phi]] + \frac{1}{2} \zeta^2 \nabla^2 \Phi] - \nabla^2 \left(\frac{1}{2} \zeta^2 \mathcal{L}[\Phi] \right), \quad (2.20)$$

$$Q_4 = -\mathcal{L} \left[\zeta \mathcal{L}[\zeta \mathcal{L}[\zeta \mathcal{L}[\Phi]] + \frac{1}{2} \zeta^2 \nabla^2 \Phi] + \frac{1}{2} \zeta^2 \nabla^2 (\zeta \mathcal{L}[\Phi]) - \frac{1}{6} \zeta^3 \nabla^2 \mathcal{L}[\Phi] \right. \\ \left. - \nabla^2 \left(\frac{1}{2} \zeta^2 \mathcal{L}[\zeta \mathcal{L}[\Phi]] + \frac{1}{3} \zeta^3 \nabla^2 \Phi \right) \right], \quad (2.21)$$

$$Q_5 = -\mathcal{L} \left[\zeta \mathcal{L} \left[\zeta \mathcal{L} \left[\zeta \mathcal{L}[\zeta \mathcal{L}[\Phi]] + \frac{1}{2} \zeta^2 \nabla^2 \Phi \right] + \frac{1}{2} \zeta^2 \nabla^2 (\zeta \mathcal{L}[\Phi]) - \frac{1}{6} \zeta^3 \nabla^2 \mathcal{L}[\Phi] \right] \right. \\ \left. + \frac{1}{2} \zeta^2 \nabla^2 \left(\zeta \mathcal{L}[\zeta \mathcal{L}[\Phi]] + \frac{1}{2} \zeta^2 \nabla^2 \Phi \right) - \frac{1}{6} \zeta^3 \nabla^2 \mathcal{L}[\zeta \mathcal{L}[\Phi]] - \frac{1}{24} \zeta^4 \nabla^2 \nabla^2 \Phi \right. \\ \left. - \nabla^2 \left(\frac{1}{2} \zeta^2 \mathcal{L} \left[\zeta \mathcal{L}[\zeta \mathcal{L}[\Phi]] + \frac{1}{2} \zeta^2 \nabla^2 \Phi \right] + \frac{1}{3} \zeta^3 \nabla^2 (\zeta \mathcal{L}[\Phi]) - \frac{1}{8} \zeta^4 \nabla^2 \mathcal{L}[\Phi] \right) \right], \quad (2.22)$$

$$R_1 = -g \zeta, \quad (2.23)$$

$$R_2 = -\frac{1}{2} \nabla \Phi \cdot \nabla \Phi + \frac{1}{2} (\mathcal{L}[\Phi])^2, \quad (2.24)$$

$$R_3 = \mathcal{L}[\Phi] \left(\mathcal{L}[\zeta \mathcal{L}[\Phi]] + \zeta \nabla^2 \Phi \right), \quad (2.25)$$

$$R_4 = \mathcal{L}[\Phi] \mathcal{L} \left[\zeta \mathcal{L}[\zeta \mathcal{L}[\Phi]] + \frac{1}{2} \zeta^2 \nabla^2 \Phi \right] + \nabla^2 \left[\frac{1}{4} \zeta^2 (\mathcal{L}[\Phi])^2 \right] + \frac{1}{2} \left(\mathcal{L}[\zeta \mathcal{L}[\Phi]] + \zeta \nabla^2 \Phi \right)^2 \\ + \frac{1}{2} \zeta (\nabla^2 \zeta) (\mathcal{L}[\Phi])^2 - \frac{1}{2} \zeta^2 (\nabla \mathcal{L}[\Phi])^2, \quad (2.26)$$

$$R_5 = \mathcal{L}[\Phi] \mathcal{L} \left[\zeta \mathcal{L} \left[\zeta \mathcal{L}[\zeta \mathcal{L}[\Phi]] + \frac{1}{2} \zeta^2 \nabla^2 \Phi \right] + \frac{1}{2} \zeta^2 \nabla^2 (\zeta \mathcal{L}[\Phi]) - \frac{1}{6} \zeta^3 \nabla^2 \mathcal{L}[\Phi] \right] \\ + \nabla^2 \left(\frac{1}{2} \zeta^2 \mathcal{L}[\Phi] \mathcal{L}[\zeta \mathcal{L}[\Phi]] + \frac{1}{3} \zeta^3 \mathcal{L}[\Phi] \nabla^2 \Phi \right) - \zeta^2 (\nabla \mathcal{L}[\Phi]) \cdot (\nabla \mathcal{L}[\zeta \mathcal{L}[\Phi]] + \frac{2}{3} \zeta \nabla (\nabla^2 \Phi)) \\ + \frac{1}{6} \zeta^3 (\nabla^2 \mathcal{L}[\Phi]) (\nabla^2 \Phi) + \left(\mathcal{L}[\zeta \mathcal{L}[\Phi]] + \zeta \nabla^2 \Phi \right) \left(\mathcal{L}[\zeta \mathcal{L}[\zeta \mathcal{L}[\Phi]] + \frac{1}{2} \zeta^2 \nabla^2 \Phi] + \frac{1}{2} \zeta (\nabla^2 \zeta) \mathcal{L}[\Phi] \right). \quad (2.27)$$

The expressions of the corresponding Hamiltonians E_n ($n = 2, \dots, 6$) are explicitly given by

$$E_2 = \frac{1}{2} \int \left(g \zeta^2 - \Phi \mathcal{L}[\Phi] \right) d\mathbf{x}, \quad (2.28)$$

$$E_3 = \frac{1}{2} \int \left\{ \zeta \nabla \Phi \cdot \nabla \Phi - \zeta (\mathcal{L}[\Phi])^2 \right\} d\mathbf{x}, \quad (2.29)$$

$$E_4 = -\frac{1}{2} \int \zeta \mathcal{L}[\Phi] \left(\mathcal{L}[\zeta \mathcal{L}[\Phi]] + \zeta \nabla^2 \Phi \right) d\mathbf{x}, \quad (2.30)$$

$$E_5 = -\frac{1}{2} \int \left\{ \zeta \left(\mathcal{L}[\zeta \mathcal{L}[\Phi]] \right)^2 + \frac{1}{3} \zeta^3 \left(\nabla^2 \Phi \right)^2 + \zeta \mathcal{L}[\Phi] \left(\mathcal{L} \left[\zeta^2 \nabla^2 \Phi \right] + \frac{1}{2} \zeta \nabla^2 (\zeta \mathcal{L}[\Phi]) - \frac{1}{6} \zeta^2 \nabla^2 \mathcal{L}[\Phi] \right) \right\} d\mathbf{x}, \quad (2.31)$$

$$E_6 = -\frac{1}{2} \int \left\{ \zeta \mathcal{L} \left[\zeta \mathcal{L} \left[\zeta \mathcal{L}[\Phi] \right] \right] \left(\mathcal{L}[\zeta \mathcal{L}[\Phi]] + \zeta \nabla^2 \Phi \right) + \mathcal{L}[\zeta \mathcal{L}[\Phi]] \left(\zeta^2 \nabla^2 (\zeta \mathcal{L}[\Phi]) - \frac{1}{3} \zeta^3 \nabla^2 \mathcal{L}[\Phi] \right) + \left(\frac{1}{2} \zeta^2 \nabla^2 \Phi \right) \mathcal{L} \left[\frac{1}{2} \zeta^2 \nabla^2 \Phi \right] + \zeta^2 \mathcal{L}[\Phi] \left(\frac{1}{2} \nabla^2 \left(\zeta^2 \nabla^2 \Phi \right) - \frac{1}{12} \zeta^2 \nabla^2 \left(\nabla^2 \Phi \right) \right) \right\} d\mathbf{x}. \quad (2.32)$$

When truncated at $O(\epsilon^3)$, the system given by (2.17) becomes the third-order system obtained by Choi (1995), who showed that the truncated system also preserves the Hamiltonian structure. Likewise, it can be shown that the fifth-order model given by (2.17) is a Hamiltonian system.

3 Spectral Formulation

3.1 System for continuous spectrum

To obtain a nonlinear system in spectral space, ζ and Φ are expressed as

$$\zeta(\mathbf{x}, t) = \int a(\mathbf{k}, t) e^{-i\mathbf{k} \cdot \mathbf{x}} d\mathbf{k}, \quad \Phi(\mathbf{x}, t) = \int b(\mathbf{k}, t) e^{-i\mathbf{k} \cdot \mathbf{x}} d\mathbf{k}, \quad (3.1)$$

where $a(\mathbf{k}, t)$ and $b(\mathbf{k}, t)$ representing the Fourier transforms of ζ and Φ , respectively. Notice that $a(-\mathbf{k}, t) = a^*(\mathbf{k}, t)$ and $b(-\mathbf{k}, t) = b^*(\mathbf{k}, t)$, with the asterisks representing the complex conjugates, as ζ and Φ are real-valued functions.

One way to find such a system is to take the Fourier transform of (2.5), which would yield the nonlinear evolution equations for $a(\mathbf{k}, t)$ and $b(\mathbf{k}, t)$ as

$$\frac{\partial a}{\partial t} - kTb = \sum_{n=2}^{\infty} q_n, \quad \frac{\partial b}{\partial t} + ga = \sum_{n=2}^{\infty} r_n, \quad (3.2)$$

where q_n and r_n representing the Fourier transforms of Q_n and R_n given by (2.6)–(2.7) can be written as

$$q_n = \iint \cdots \int \alpha_{0,1,\dots,n}^{(n)} b_1 a_2 a_3 \cdots a_n \delta_{0-1-\dots-n} d\mathbf{k}_1 d\mathbf{k}_2 \cdots d\mathbf{k}_n, \quad (3.3)$$

$$r_n = \iint \cdots \int \beta_{0,1,\dots,n}^{(n)} b_1 b_2 a_3 \cdots a_n \delta_{0-1-\dots-n} d\mathbf{k}_1 d\mathbf{k}_2 \cdots d\mathbf{k}_n. \quad (3.4)$$

In (3.3)–(3.4), we have used the following short-hand notations

$$a_j = a(\mathbf{k}_j, t), \quad b_j = b(\mathbf{k}_j, t), \quad \delta_{j-l} = \delta(\mathbf{k}_j - \mathbf{k}_l), \quad \mathbf{k}_0 = \mathbf{k}, \quad (3.5)$$

where δ is the Dirac delta function. Under the third-order approximation, the system given by (3.2) was derived first by Zakharov (1968) for infinitely deep water and by Stiassnie & Shemer (1984) for finite depth water. The system has been also extended to $O(\epsilon^4)$ by Stiassnie & Shemer (1984).

Although it is straightforward, finding the explicit expressions of $\alpha_{0,1,\dots,n}^{(n)}$ and $\beta_{0,1,\dots,n}^{(n)}$ by taking the Fourier transform of (2.5) is lengthy and cumbersome, in particular, as the order

of nonlinearity increases. An alternative and more convenient way is to use the Hamiltonian, as shown by Krasitskii (1994), whose approach will be adopted here to obtain the fifth-order system. From (2.16), the n -th order Hamiltonian $H_n = E_n/(2\pi)^2$ can be written in spectral space as

$$H_2 = \frac{1}{2} \iint (g a_1 a_2 + k_1 T_1 b_1 b_2) \delta_{1+2} d\mathbf{k}_1 d\mathbf{k}_2, \quad (3.6)$$

$$H_n = \frac{1}{2} \iint \dots \int h_{1,2,3,\dots,n}^{(n)} b_1 b_2 a_3 \dots a_n \delta_{1+\dots+n} d\mathbf{k}_1 d\mathbf{k}_2 d\mathbf{k}_3 \dots d\mathbf{k}_n \quad \text{for } n \geq 3. \quad (3.7)$$

For example, under the fifth-order approximation, $h_{1,2,3,\dots,n}^{(n)}$ for $n = 3, 4, 5, 6$ can be written explicitly as

$$h_{1,2,3}^{(3)} = -(\mathbf{k}_1 \cdot \mathbf{k}_2 + \theta_1 \theta_2), \quad (3.8)$$

$$h_{1,2,3,4}^{(4)} = -\left(k_2^2 \theta_1 - \theta_1 \theta_2 \theta_{2+3}\right), \quad (3.9)$$

$$h_{1,2,3,4,5}^{(5)} = -\left[\left(\frac{1}{6}k_2^2 - \frac{1}{2}k_{2+3}^2 + \theta_{1+3} \theta_{2+4}\right) \theta_1 \theta_2 - k_2^2 \theta_1 \theta_{2+3+4} + \frac{1}{3}k_1^2 k_2^2\right], \quad (3.10)$$

$$h_{1,2,3,4,5,6}^{(6)} = \left[\left(\theta_1 \theta_{1+3} - k_1^2\right) \theta_2 \theta_{2+4} \theta_{2+4+5} + \left(\frac{1}{3}k_2^2 - k_{2+4}^2\right) \theta_1 \theta_2 \theta_{1+3} + \frac{1}{4}k_1^2 k_2^2 \theta_{2+5+6} + \frac{1}{2}k_1^2 k_{1+3+4}^2 \theta_2 - \frac{1}{12}k_1^4 \theta_2\right], \quad (3.11)$$

where

$$k_j = |\mathbf{k}_j|, \quad \theta_j = k_j T_j, \quad T_j = \tanh(k_j h), \quad k_{m+n} = |\mathbf{k}_m + \mathbf{k}_n|, \quad T_{m+n} = \tanh(k_{m+n} h). \quad (3.12)$$

The evolution equations for $a(\mathbf{k}, t)$ and $b(\mathbf{k}, t)$ can be then obtained from Hamilton's equations:

$$\frac{\partial a}{\partial t} = \frac{\delta H}{\delta b^*}, \quad \frac{\partial b}{\partial t} = -\frac{\delta H}{\delta a^*}. \quad (3.13)$$

From (3.6)–(3.7) and (3.13), the expressions of $\alpha_{0,1,\dots,n}^{(n)}$ and $\beta_{0,1,\dots,n}^{(n)}$ in (3.3)–(3.4) are found, in terms of $h_{1,2,3,\dots,n}^{(n)}$, as

$$\alpha_{0,1,\dots,n}^{(n)} = \frac{1}{2} \left(h_{-0,1,2,\dots,n}^{(n+1)} + h_{1,-0,2,\dots,n}^{(n+1)} \right), \quad (3.14)$$

$$\beta_{0,1,\dots,n}^{(n)} = -\frac{1}{2} \left(h_{1,2,-0,3,\dots,n}^{(n+1)} + \dots + h_{1,2,3,\dots,n,-0}^{(n+1)} \right). \quad (3.15)$$

Notice that the interaction coefficients $h_{1,2,\dots,n}^{(n)}$ in (3.8)–(3.11) are not symmetric. In other words, except for $h_{1,2,3}^{(3)}$, they change when indices 1 and 2 are interchanged although their Hamiltonians given by (3.7) remain unchanged. This is also true for indices 3, \dots , n . Nevertheless, if necessary, they can be easily made symmetric, as shown by Krasitskii (1994).

3.2 System for discrete spectrum

When a nonlinear wave field can be represented by a superposition of discrete modes, $a(\mathbf{k}, t)$ and $b(\mathbf{k}, t)$ can be written as

$$a(\mathbf{k}, t) = \sum_{\mathbf{j}} \delta(\mathbf{k} - \mathbf{k}_{\mathbf{j}}) a_{\mathbf{j}}(t), \quad b(\mathbf{k}, t) = \sum_{\mathbf{j}} \delta(\mathbf{k} - \mathbf{k}_{\mathbf{j}}) b_{\mathbf{j}}(t), \quad (3.16)$$

where $\mathbf{k}_{-j} = -\mathbf{k}_j$. In (3.16), the summations should be in general taken over all discrete modes involved in nonlinear wave interactions unless an additional approximation is made.

When truncated at $O(\epsilon^M)$, the amplitude equations for a_j and b_j under the M -th order approximation are given, from (3.2), by

$$\frac{da_j}{dt} - k_j T_j b_j = \sum_{n=2}^M \left[\sum_{\mathbf{j}_1, \mathbf{j}_2, \dots, \mathbf{j}_n} \alpha_{\mathbf{j}, \mathbf{j}_1, \dots, \mathbf{j}_n}^{(n)} b_{\mathbf{j}_1} a_{\mathbf{j}_2} a_{\mathbf{j}_3} \cdots a_{\mathbf{j}_n} \delta_{0-1-\dots-n} \right], \quad (3.17)$$

$$\frac{db_j}{dt} + g a_j = \sum_{n=2}^M \left[\sum_{\mathbf{j}_1, \mathbf{j}_2, \dots, \mathbf{j}_n} \beta_{\mathbf{j}, \mathbf{j}_1, \dots, \mathbf{j}_n}^{(n)} b_{\mathbf{j}_1} b_{\mathbf{j}_2} a_{\mathbf{j}_3} \cdots a_{\mathbf{j}_n} \delta_{0-1-\dots-n} \right], \quad (3.18)$$

where $\delta_{0-1-\dots-n} = \delta_{\mathbf{j}-\mathbf{j}_1-\dots-\mathbf{j}_n}$. The corresponding Hamiltonians are given by

$$H_2 = \frac{1}{2} \sum_{\mathbf{j}_1} \sum_{\mathbf{j}_2} (g a_{\mathbf{j}_1} a_{\mathbf{j}_2} + k_{\mathbf{j}_1} T_{\mathbf{j}_1} b_{\mathbf{j}_1} b_{\mathbf{j}_2}) \delta_{1+2}, \quad (3.19)$$

$$H_n = \frac{1}{2} \sum_{\mathbf{j}_1, \mathbf{j}_2, \dots, \mathbf{j}_n} h_{\mathbf{j}, \mathbf{j}_1, \dots, \mathbf{j}_n}^{(n)} b_{\mathbf{j}_1} b_{\mathbf{j}_2} a_{\mathbf{j}_3} \cdots a_{\mathbf{j}_n} \delta_{1+2+\dots+n}, \quad (3.20)$$

from which the amplitude equations given by (3.17)–(3.18) can be obtained from the Hamilton's equations:

$$\frac{\partial a_j}{\partial t} = \frac{\partial H}{\partial b_j^*}, \quad \frac{\partial b_j}{\partial t} = -\frac{\partial H}{\partial a_j^*}, \quad (3.21)$$

where $H = \sum_n H_n$. For $M = 5$, the expressions of $h_{\mathbf{j}, \mathbf{j}_1, \dots, \mathbf{j}_n}^{(n)}$ are defined by (3.8)–(3.11) and $\alpha_{\mathbf{j}, \mathbf{j}_1, \dots, \mathbf{j}_n}^{(n)}$ and $\beta_{\mathbf{j}, \mathbf{j}_1, \dots, \mathbf{j}_n}^{(n)}$ are given by (3.14)–(3.15).

When $\mathbf{k}_j = (jK_x, lK_y)$, (3.16) represent the Fourier series of ζ and Φ and equations (3.17)–(3.18) determine their evolution of the Fourier coefficients, a_j and b_j . If a finite number of Fourier modes are used for numerical computations, solving the ordinary differential equations given by (3.17)–(3.18) is equivalent to solving (2.5) using the pseudo-spectral method described in §2.2. Unfortunately, the evaluation of the right-hand sides is computationally expensive and, therefore, solving a dynamical system is in general less effective than the pseudo-spectral method based on FFT.

3.3 Time-periodic solutions of the third-order spectral model

Under the third-order approximation ($M = 3$), the amplitude equations for a_j and b_j can be written, from (3.17)–(3.18), as

$$\begin{aligned} \frac{da_j}{dt} &= k_j T_j b_j + \sum_{\mathbf{j}_1, \mathbf{j}_2} \left(\mathbf{k}_j \cdot \mathbf{k}_{\mathbf{j}_1} - k_j T_j k_{\mathbf{j}_1} T_{\mathbf{j}_1} \right) b_{\mathbf{j}_1} a_{\mathbf{j}_2} \delta_{0-1-2} \\ &\quad + \sum_{\mathbf{j}_1, \mathbf{j}_2, \mathbf{j}_3} \left[k_j T_j \left(k_{\mathbf{j}_1} T_{\mathbf{j}_1} k_{\mathbf{j}_1+\mathbf{j}_2} T_{\mathbf{j}_1+\mathbf{j}_2} - \frac{1}{2} k_{\mathbf{j}_1}^2 \right) - \frac{1}{2} k_j^2 k_{\mathbf{j}_1} T_{\mathbf{j}_1} \right] b_{\mathbf{j}_1} a_{\mathbf{j}_2} a_{\mathbf{j}_3} \delta_{0-1-2-3}, \quad (3.22) \\ \frac{db_j}{dt} &= -g a_j + \sum_{\mathbf{j}_1, \mathbf{j}_2} \frac{1}{2} \left(\mathbf{k}_{\mathbf{j}_1} \cdot \mathbf{k}_{\mathbf{j}_2} + k_{\mathbf{j}_1} T_{\mathbf{j}_1} k_{\mathbf{j}_2} T_{\mathbf{j}_2} \right) b_{\mathbf{j}_1} b_{\mathbf{j}_2} \delta_{0-1-2} \end{aligned}$$

RIMS Workshop on Nonlinear Water Waves

$$+ \sum_{\mathbf{j}_1, \mathbf{j}_2, \mathbf{j}_3} \left[k_{\mathbf{j}_1} T_{\mathbf{j}_1} \left(-k_{\mathbf{j}_2} T_{\mathbf{j}_2} k_{\mathbf{j}-\mathbf{j}_1} T_{\mathbf{j}-\mathbf{j}_1} + k_{\mathbf{j}_2}^2 \right) \right] b_{\mathbf{j}_1} b_{\mathbf{j}_2} a_{\mathbf{j}_3} \delta_{0-1-2-3}. \quad (3.23)$$

When we assume that the waves are propagating in the x -direction so that $\mathbf{k}_j = (k_j, 0)$ with $k_j = jk$ and $(a_j, b_j) = (a_j, b_j)$, equations (3.22)–(3.23) describe the evolution of the Fourier coefficients of ζ and Φ . Furthermore, we assume that the first harmonics are initially dominant and all other higher-harmonics are excited through nonlinearity so that

$$a_j = O(\epsilon), \quad a_0 = O(b_0) = O(b_{2j}) = O(a_{2j}) = O(\epsilon^2), \quad a_{3j} = O(b_{3j}) = O(\epsilon^3). \quad (3.24)$$

Then, the third-order system (3.22)–(3.23) can be approximated by four ordinary differential equations: for the j -th mode,

$$\begin{aligned} \frac{da_j}{dt} - k_j T_j b_j &= 2k_j^2 (1 - T_j T_{2j}) a_j^* b_{2j} - k_j^2 (1 + T_j^2) a_{2j} b_j^* \\ &\quad - 2k_j^3 T_j (1 - T_j T_{2j}) |a_j|^2 b_j - k_j^3 T_j a_j^2 b_j^*, \end{aligned} \quad (3.25)$$

$$\frac{db_j}{dt} + g a_j = -2k_j^2 (1 - T_j T_{2j}) b_j^* b_{2j} + 2k_j^3 T_j (1 - T_j T_{2j}) a_j |b_j|^2 + k_j^3 T_j a_j^* b_j^2, \quad (3.26)$$

and, for the $2j$ -th mode,

$$\frac{da_{2j}}{dt} - k_{2j} T_{2j} b_{2j} = 2k_j^2 (1 - T_j T_{2j}) a_j b_j, \quad (3.27)$$

$$\frac{db_{2j}}{dt} + g a_{2j} = \frac{1}{2} k_j^2 (1 + T_j^2) b_j^2. \quad (3.28)$$

The Hamiltonian for the system is given, by imposing (3.24) to (3.19)–(3.20), by

$$\begin{aligned} H &= \left(g |a_j|^2 + k_j T_j |b_j|^2 \right) + \left(g |a_{2j}|^2 + k_{2j} T_{2j} |b_{2j}|^2 \right) \\ &\quad + \frac{1}{2} \left[h_{j,j,-2j}^{(3)} b_j^2 a_{2j}^* + h_{-j,-j,2j}^{(3)} b_j^{*2} a_{2j} + 2h_{2j,-j,-j}^{(3)} b_{2j} b_j^* a_j^* + 2h_{-2j,j,j}^{(3)} b_{2j}^* b_j a_j \right] \\ &\quad + \frac{1}{2} \left[h_{j,j,-j,-j}^{(4)} b_j^2 a_j^{*2} + h_{-j,-j,j,j}^{(4)} b_j^{*2} a_j^2 \right. \\ &\quad \quad \left. + \left(h_{j,-j,j,-j}^{(4)} + h_{j,-j,-j,j}^{(4)} + h_{-j,j,j,-j}^{(4)} + h_{-j,j,-j,j}^{(4)} \right) |b_j|^2 |a_j|^2 \right] \\ &= \left(g |a_j|^2 + k_j T_j |b_j|^2 \right) + \left(g |a_{2j}|^2 + k_{2j} T_{2j} |b_{2j}|^2 \right) \\ &\quad - \frac{1}{2} k_j^2 (1 + T_j^2) \left(b_j^2 a_{2j}^* + b_j^{*2} a_{2j} \right) + 2k_j^2 (1 - T_j T_{2j}) \left(b_{2j} b_j^* a_j^* + b_{2j}^* b_j a_j \right) \\ &\quad - \frac{1}{2} k_j^3 T_j \left(b_j^2 a_j^{*2} + b_j^{*2} a_j^2 \right) - 2k_j^3 T_j (1 - T_j T_{2j}) |b_j|^2 |a_j|^2, \end{aligned} \quad (3.29)$$

where we have used $h_{2j,-j,-j}^{(3)} = h_{-j,2j,-j}^{(3)}$ and $h_{-2j,j,j}^{(3)} = h_{j,-2j,j}^{(3)}$. Here the amplitude equations of the third-harmonics (a_{3j} and b_{3j}) as not written as they have no effect on the dynamics of the first harmonics of interest unless the higher-order nonlinearity is included. Therefore, we consider only the first two harmonics here.

3.3.1 Progressive waves

When linearized, (3.25)–(3.26) can be reduced to

$$\frac{da_j}{dt} = k_j T_j b_j, \quad \frac{db_j}{dt} = -g a_j, \quad (3.30)$$

whose solution can be written as

$$a_j = \bar{a}_j e^{i\omega_j t}, \quad b_j = i (g/\omega_j) \bar{a}_j e^{i\omega_j t}, \quad (3.31)$$

so that

$$b_j = i (g/\omega_j) a_j. \quad (3.32)$$

Here $\omega_j > 0$ satisfies the linear dispersion relation (2.9):

$$\omega_j^2 = g k_j T_j. \quad (3.33)$$

At the second order, the particular solutions of (3.27)–(3.28) for the second harmonics can be obtained, using $da_{2j}/dt = 2\omega_j a_{2j}$ and $db_{2j}/dt = 2\omega_j b_{2j}$, as

$$a_{2j} = \frac{1}{\omega_{2j}^2 - 4\omega_j^2} \left[4i\omega_j k_j^2 (1 - T_j T_{2j}) a_j b_j + k_j^3 T_{2j} (1 + T_j^2) b_j^2 \right], \quad (3.34)$$

$$b_{2j} = \frac{1}{\omega_{2j}^2 - 4\omega_j^2} \left[-2gk_j^2 (1 - T_j T_{2j}) a_j b_j + i\omega_j k_j^2 (1 + T_j^2) b_j^2 \right], \quad (3.35)$$

where $\omega_{2j}^2 = gk_{2j}T_{2j}$ is the natural frequency of the second harmonics of wavenumber $k_{2j} = 2k_j$ and we have assumed that $\omega_{2j} \neq 2\omega_j$. When substituting the linear solution (3.31) into (3.34)–(3.35), the second harmonic solutions can be found as

$$a_{2j} = \alpha_{2j} \bar{a}_j^2 e^{2i\omega_j t}, \quad \alpha_{2j} = gk_j^2 \left(\frac{4 - 3T_j T_{2j} + T_{2j}/T_j}{4\omega_j^2 - \omega_{2j}^2} \right) = k_j \left(\frac{3 - T_j^2}{2T_j^3} \right), \quad (3.36)$$

$$b_{2j} = i\beta_{2j} \bar{a}_j^2 e^{2i\omega_j t}, \quad \beta_{2j} = \frac{g^2 k_j^2}{\omega_j} \left(\frac{3 - 2T_j T_{2j} + T_j^2}{4\omega_j^2 - \omega_{2j}^2} \right) = \omega_j \left(\frac{3 + T_j^4}{4T_j^4} \right), \quad (3.37)$$

where we have used, for the last expressions of α_{2j} and β_{2j} ,

$$T_{2j} = 2T_j/(1 + T_j^2). \quad (3.38)$$

From (3.31), a_{2j} and b_{2j} given by (3.36)–(3.37) can be expressed, in terms of a_j and b_j , as

$$a_{2j} = \alpha_{2j} a_j^2 + O(\epsilon^3), \quad b_{2j} = i\beta_{2j} a_j^2 + O(\epsilon^3). \quad (3.39)$$

To study the nonlinear behavior of the first harmonics (a_j and b_j), although not necessary, it is convenient to use a single amplitude equation, for example, for a_j . After substituting (3.32) and (3.39) into the right-hand sides of (3.25)–(3.26), the time evolution equation for a_j correct to $O(\epsilon^3)$ can be found as

$$\frac{d^2 a_j}{dt^2} + \omega_j^2 \left(1 + \alpha_j |a_j|^2 \right) a_j = 0, \quad (3.40)$$

where α_j is given by

$$\alpha_j = k_j^2 \left[\frac{16 T_j + (1 - 18 T_j^2 + 9 T_j^4) T_{2j}}{2 T_j (2 T_j - T_{2j})} \right] = k_j^2 \left(\frac{9 T_j^4 - 10 T_j^2 + 9}{2 T_j^3} \right) > 0. \quad (3.41)$$

Similarly, the amplitude equation for b_j can be found as

$$\frac{d^2 b_j}{dt^2} + \omega_j^2 (1 + \beta_j |b_j|^2) b_j = 0, \quad \beta_j = (\omega_j^2 / g^2) \alpha_j. \quad (3.42)$$

For a time-periodic solution of (3.40), $a_j(t)$ is written as

$$a_j(t) = A_j e^{i\Omega_j t}, \quad \Omega_j = \omega_j [1 + \delta_j + O(\epsilon^4)], \quad (3.43)$$

where $\delta = O(\epsilon^2)$ is the nonlinear correction to the wave frequency. By substituting (3.43) into (3.40), one can find, at the order of $O(\epsilon^3)$, that

$$\delta_j = \frac{1}{2} \alpha_j A_j^2 = \left(\frac{9 T_j^4 - 10 T_j^2 + 9}{4 T_j^3} \right) k_j^2 A_j^2, \quad (3.44)$$

which is the nonlinear frequency correction of Stokes waves in water of finite depth, as shown, for example, in Whitham (1976, §13.13). As a special case, for infinitely deep water ($T_j \rightarrow 1$ and $T_{2j} \rightarrow 1$), the expression of α_j , δ_j , and a_{2j} are given by

$$\alpha_j = 4k_j^2, \quad \delta_j = 2k_j^2 A_j^2, \quad a_{2j} = k_j A_j^2 e^{2i\omega_j t}. \quad (3.45)$$

This solution corresponds to that of Stokes (1847), where the wave amplitude \bar{a}_j is defined as $\bar{a}_j = 2A_j$ so that $\delta_j = k_j^2 \bar{a}_j^2 / 2$.

3.3.2 Standing waves

For standing wave solutions, we must have

$$a_j = a_{-j} = a_j^*, \quad b_j = b_{-j} = b_j^*, \quad a_0 = 0, \quad (3.46)$$

so that ζ and Φ can be written as

$$\zeta(x, t) = 2 \sum_{j \geq 0} a_j(t) \cos(k_j x), \quad \Phi(x, t) = 2 \sum_{j \geq 0} b_j(t) \cos(k_j x), \quad (3.47)$$

which satisfy the side-wall boundary conditions at $x = 0$ and L with

$$k_j = j\pi/L, \quad (3.48)$$

where L is the tank length. Then, as a_j and b_j are real, their evolution equations are given, from (3.22)–(3.23), or directly from (3.25)–(3.26), by

$$\frac{da_j}{dt} - k_j T_j b_j = 2k_j^2 (1 - T_j T_{2j}) a_j b_{2j} - k_j^2 (1 + T_j^2) a_{2j} b_j - k_j^3 T_j (3 - 2T_j T_{2j}) a_j^2 b_j, \quad (3.49)$$

$$\frac{db_j}{dt} + g a_j = -2k_j^2 (1 - T_j T_{2j}) b_j b_{2j} + k_j^3 T_j (3 - 2T_j T_{2j}) a_j b_j^2, \quad (3.50)$$

while the time evolution of the second harmonics a_{2j} and b_{2j} are governed by (3.27)–(3.28).

When we linearize (3.49)–(3.50), the leading-order solutions can be found as

$$a_j = A_j e^{i\omega_j t} + C.C., \quad b_j = i(g/\omega_j) A_j e^{i\omega_j t} + C.C., \quad (3.51)$$

where the complex conjugates (*C.C.*) are needed as a_j and b_j are real functions. At the second-order, the particular solutions of (3.27)–(3.28) for the second harmonics can be found as

$$a_{2j} = \left(\alpha_{2j} A_j^2 e^{2i\omega_j t} + C.C. \right) + \gamma_{2j} |A_j|^2, \quad b_{2j} = \left(i\beta_{2j} A_j^2 e^{2i\omega_j t} + C.C. \right), \quad (3.52)$$

with α_{2j} , β_{2j} , and γ_{2j} given by

$$\alpha_{2j} = k_j \left(\frac{3 - T_j^2}{2T_j^3} \right), \quad \beta_{2j} = \frac{gk_j}{\omega_j} \left(\frac{3 + T_j^4}{4T_j^3} \right), \quad \gamma_{2j} = k_j \left(\frac{1 + T_j^2}{T_j} \right). \quad (3.53)$$

For standing waves, since it is not possible to write a_{2j} and b_{2j} in terms of a_j or b_j , the system cannot be reduced to a single equation for a_j or b_j . Therefore, in general, it is necessary to solve the system given by (3.49)–(3.50) along with (3.27)–(3.28), except for the infinitely deep water case, for which $a_{2j} = k_j a_j^2$ as $\alpha_{2j} = k_j$ and $\gamma_{2j} = 2k_j$.

For a time-periodic solution, we write a_j and b_j as

$$a_j = A_j e^{i\Omega_j t} + A_{3j} e^{3i\Omega_j t} + C.C. + O(\epsilon^5), \quad \Omega_j = \omega_j \left[1 + \delta_j + O(\epsilon^4) \right] + O(\epsilon^5), \\ b_j = B_j e^{i\Omega_j t} + B_{3j} e^{3i\Omega_j t} + C.C. + O(\epsilon^5),$$

where $A_j = O(\epsilon)$, $B_j = O(\epsilon)$, $A_{3j} = O(\epsilon^3)$, $B_{3j} = O(\epsilon^3)$, and $\delta_j = O(\epsilon^2)$ have been assumed real. By substituting (3.54)–(3.55) into (3.49)–(3.50) with (3.52), the nonlinear correction to the wave frequency can be determined at $O(\epsilon^3)$ as

$$\delta_j = \left(\frac{9 - 12T_j^2 - 3T_j^4 - 2T_j^6}{4T_j^4} \right) k_j^2 A_j^2, \quad (3.56)$$

which has been obtained by Tadjbakhsh & Keller (1960). As pointed out by Tadjbakhsh & Keller (1960), δ_j is negative for $k_j h > 1.058$, implying that the frequency decreases as the wave amplitude increases, which is observed for a soft spring. On the other hand, for $k_j h < 1.058$, δ_j is positive, which corresponds to the case of a hard spring.

For infinitely deep water ($h \rightarrow \infty$, $T_j \rightarrow 1$), (3.56) can be reduced to $\delta_j = -2k_j^2 A_j^2$, which is the result obtained by Rayleigh (1915), where the wave amplitude is defined as $\bar{a}_j = 4A_j$ so that $\delta_j = -k_j^2 \bar{a}_j^2 / 8$.

4 Conclusion

Using the equivalence between the spectral formulation of Zakharov (1968) and the pseudo-spectral formulation of West *et al.* (1968), we obtain an explicit fifth-order spectral model that governs the evolution of the Fourier transforms of the surface elevation ζ and the free surface velocity potential Φ . Compared with a lower-order one, the fifth-order model would improve

the description of the spectral evolution of broadband nonlinear waves of finite amplitudes. When discretized, the model provides a dynamical system for any number of discrete modes, which would be useful to study nonlinear standing waves in a sloshing tank. Although only the third-order solutions for traveling and standing waves have been presented, the fifth-order time-periodic solutions can be easily obtained from the model presented here. It should be remarked that, as the higher-order Hamiltonians are also available from the pseudo-spectral formulation of *West et al.* (1987) via recursion formulas, it is straightforward to find a higher-order spectral model although it would be complicated.

Acknowledgements

The author gratefully acknowledges support from the US National Science Foundation through Grant No. DMS-1517456 and OCE-1634939.

References

- [1] Annenkov, S. Y. and Shrira, V. I. 2001 Numerical modelling of water-wave evolution based on the Zakharov equation. *J. Fluid Mech.* **449**, 341–371.
- [2] Bateman, W. J. D., Swan, C. and Taylor, P. H. 2001 On the efficient numerical simulation of directionally spread surface water waves. *J. Comput. Phys.* **174**, 277–305.
- [3] Choi, W. 1995 Nonlinear evolution equations for two-dimensional waves in a fluid of finite depth. *J. Fluid Mech.* **295**, 381–394.
- [4] Choi, W., Kent, C. P. and Schillinger, C. J. 2005 Numerical modeling of nonlinear surface waves and its validation, *Advances in Engineering Mechanics - Reflections and outlooks in honor of Theodore Y.-T. Wu*, ed. by A. T. Chwang, M. H. Teng & D. T. Valentine, 94–110, World Scientific.
- [5] Craig, W. and Sulem, C. 1993 Numerical simulation of gravity waves. *J. Comput. Phys.* **108**, 73–83.
- [6] Dommermuth, D. G. and Yue, D. K. P. 1987 A high-order spectral method for the study of nonlinear gravity waves. *J. Fluid Mech.* **184**, 267–288.
- [7] Clamond, D. and Grue, J. 2001 A fast method for fully nonlinear water-wave computations. *J. Fluid Mech.* **447**, 337–355.
- [8] Goulet, A. and Choi, W. 2011 Nonlinear evolution of irregular surface waves: comparison of numerical solutions with laboratory experiments for long crested waves. *Phys. Fluids* **23**, 016601.
- [9] Krasitskii, V. P. 1994 On reduced equations in the Hamiltonian theory of weakly nonlinear surface waves. *J. Fluid Mech.* **272**, 1–20.

- [10] Mei, C. C., Stiassnie, M. and Yue, D. K.-P. 2005 *Theory and applications of ocean surface waves. Part 2: Nonlinear Aspects*. World Scientific.
- [11] Lord Rayleigh, J. W. S. 1915 Deep water waves, progressive or stationary, to the third order of approximation. *Proc. Roy. Soc. Lond. A* **91**, 345–353.
- [12] Stiassnie, M. & Shemer, L. 1984. On modifications of the Zakharov equation for surface gravity waves. *J. Fluid Mech.* **143**, 47–67.
- [13] Stokes, G. G. 1847 On the theory of oscillating waves. *Trans. Cambridge Philos. Soc.* **8**, 441–455.
- [14] Tadjbakhsh, I. and Keller, J. B. 1960 Standing surface waves of finite amplitude. *J. Fluid Mech.* **8**, 442–451.
- [15] Tanaka, M. 2001a A method of studying nonlinear random field of surface gravity waves by direct numerical simulation. *Fluid Dyn. Res.* **28**, 41–60.
- [16] Tanaka, M. 2001b Verification of Hasselmann's energy transfer among surface gravity waves by direct numerical simulations of primitive equations. *J. Fluid Mech.* **444**, 199–221.
- [17] West, B. J., Brueckner, K. A., Janda, R. S., Milder, D. M. and Milton, R. L. 1987 A New Numerical method for Surface Hydrodynamics. *J. Geophys. Res.* **92**, 11,803–11,824.
- [18] Whitham, G. B. 1974 *Linear and nonlinear waves*. Wiley.
- [19] Yuen, H. C. and Lake, B. M. 1982 Nonlinear dynamics of deep-water gravity waves. *Adv. Appl. Mech.* **22**, 67–229.
- [20] Zakharov, V. E. 1968 Stability of periodic waves of finite amplitude on the surface of deep fluid. *J. Appl. Mech. Tech. Phys.* **9**, 190–194.