Periodic wave patterns of two-dimensional Boussinesq systems

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Abstract

We prove the existence of a large family of two-dimensional travelling wave patterns for a Boussinesq system which describes three-dimensional water waves. This model equation results from full Euler equations in assuming that the depth of the fluid layer is small with respect to the horizontal wave length, and that the flow is potential, with a free surface without surface tension. Our proof uses the Lyapunov–Schmidt method which may be managed here, contrary to the case of gravity waves with full Euler equations. Our results are in a good qualitative agreement with experimental results.

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1. Introduction

To describe small-amplitude and long wavelength (the depth is small with respect to wave length) gravity waves of an ideal, incompressible liquid, the system

\[
\begin{align*}
\eta_t + \nabla \cdot \mathbf{v} + \nabla \cdot (\eta \mathbf{v}) - \frac{1}{6} \Delta \eta_t &= 0, \\
\mathbf{v}_t + \nabla \eta + \frac{1}{2} \nabla |\mathbf{v}|^2 - \frac{1}{6} \Delta \mathbf{v}_t &= 0
\end{align*}
\]

was put forward by Bona, Colin, Lannes [1], where the horizontal location \(x\) and time \(t\) are scaled by \(h_0\) and \(\sqrt{h_0/g}\), \(\eta(x, t)\) and \(\mathbf{v}(x, t)\) are scaled by \(h_0\) and \(\sqrt{gh_0}\) respectively, with \(g\) being the acceleration of gravity and \(h_0\) being the average water depth. The unknown functions \(\eta(x, t)\) and \(\mathbf{v}(x, t)\) represent the dimensionless deviation of the water surface from its undisturbed position and the horizontal velocity at the level of \(\sqrt{2/3}h_0\) of the depth of the undisturbed fluid, respectively. The derivation of (1) is similar to its one-dimensional version, which is given in detail in [2].

The study of two-dimensional wave patterns has been evolved around the KP equation since KP equation admits such solutions explicitly, assuming that the nonlinear waves are nearly one-dimensional. Genuinely two-dimensional nonlinear waves are observed experimentally (that is three-dimensional waves with two-dimensional free surface) outside the putative range of validity of the KP equation [3]. Since the system (1) is derived without the KP assumptions

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that the wave is nearly one-dimensional and predominantly in one-direction, the travelling two-dimensional wave patterns of system (1) are genuinely two-dimensional. The existence of such wave patterns is proved using the bifurcation theory with the bifurcation parameter being the phase velocity. To our knowledge, for the full Euler equations, there exist existence results for doubly periodic horizontally two-dimensional travelling waves, only in presence of surface tension (see for example [4–7]). In the case of no surface tension, one can find extensive numerical results (in putting the surface tension equal to 0) reported in [8]. Our result on system (1) which has no surface tension agrees qualitatively with the results in [8] in the appropriate parameter region. We note here that system (1) can be modified, such as adding a term \(-\tau \nabla \Delta \eta \) or \(\tau \Delta \eta \) on the left-hand side of the second equation, where \(\tau = \Gamma/\rho gh^2\) is the Bond number with \(\Gamma\) being the surface tension coefficient and \(\rho\) being the density of water, to describe waves with surface tension effects [9]. It shows that the transition from no surface tension to small surface tension is smooth, which would justify the use of no surface tension models for water waves.

We have restricted our study to the two-dimensional wave patterns which are symmetric about the direction of the propagation. For other possible choices, see the discussion in [10]. One consequence of our results is that for almost any \((k, \tau)\), where the wave lengths in the horizontal directions are \(2\pi/k\) and \(2\pi/(k\tau)\) respectively, and for small enough wave height, there is a doubly periodic wave pattern with a transport velocity which is slightly above \(c_0 = 36(1 + \tau^2)/(6 + k^2(1 + \tau^2))^2\).

It is worth to note that the problem we consider here is easier than the problem with the full Euler equations, because the operators occurring here are explicit, contrary to the Dirichlet–Neumann operator which is implicit, and because the dispersion equation is nicer in the sense that except few bad choices of the critical parameter, we can use the Lyapunov–Schmidt method, contrary to the full Euler equations where small divisors occur, in absence of surface tension (see discussion in [10]).

Structure of the paper: we set the problem of two-dimensional periodic travelling waves for the system (1) in Section 2. In Section 3 we study the linearization near the 0 equilibrium solution, discussing extensively the consequences of the structure of the dispersion relation, which allows to define a smoothing pseudo-inverse of the linearized operator (see Theorem 1). The bifurcation analysis is made at Section 4, in taking into account the symmetries of the problem. The main result is Theorem 2 which gives the existence and the form of bifurcating doubly periodic waves in function of the structure of the dispersion relation, which allows to define a smoothing pseudo-inverse of the linearized operator (see Theorem 1).

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2. Position of the problem

We are looking for solutions of system (1) under the form of 2-dimensional travelling waves, i.e. \(\eta\) and \(v\) are periodic functions of \(x - ct\), where \(x = (x_1, x_2) \in \mathbb{R}^2\), and \(c\) is the velocity of the travelling wave, which plays the role of a parameter. The periodicity is both in \(x_1\) and \(x_2\). For these solutions, the system (1) reads as

\[
\begin{align*}
\nabla \cdot (v + \eta v) - c \cdot \nabla \left( \eta - \frac{1}{6} \Delta \eta \right) &= 0, \\
\nabla \left( \eta + \frac{1}{2} |v|^2 \right) - c \cdot \nabla \left( v - \frac{1}{6} \Delta v \right) &= 0.
\end{align*}
\]

A first observation is that the subspace where \(\text{curl}(v) = 0\) is invariant under (2). This comes from the fact that the original system (1) leads to

\[
\partial_t \left\{ \text{curl} \left( v - \frac{1}{6} \Delta v \right) \right\} = 0
\]

which implies for an irrotational initial condition and due to the double periodicity of \(v\), that \(\text{curl}(v) = 0\) holds for any \(t\).

Indeed, system (2) has a first integral, coming from the identity

\[
\nabla \left( \eta + \frac{1}{2} |v|^2 - c \cdot \left( v - \frac{1}{6} \Delta v \right) \right) \cdot c = 0.
\]
from which we deduce that
\[ \eta + \frac{1}{2} |v|^2 - \mathbf{c} \cdot \left( v - \frac{1}{6} \Delta v \right) = \beta(x_2), \] (3)
where \( \beta \) is an arbitrary function of the coordinate \( x_2 \) orthogonal to the direction \( x_1 \) of the travelling wave. Moreover, if this function \( \beta \) is a constant, then, from the second equation of (2) we obtain
\[ \text{curl} \left( v - \frac{1}{6} \Delta v \right) = 0, \]
and then, because of periodicity, \( \text{curl}(v) = 0 \). Conversely, \( \text{curl}(v) = 0 \) in (2) implies that the function \( \beta \) is a constant.

Since the system (1) was derived in assuming the 3-dimensional flow to be potential, this implies that our two-dimensional vector field \( v \) satisfies
\[ \text{curl}(v) = 0. \]
So, we do not restrict the analysis in assuming from now-on that the 2-dimensional flow is potential. It is clear that we might eliminate \( \eta \) from the system (2), and derive a unique scalar equation for the velocity potential. We prefer to stay with the above formulation (2), since the operators are simpler, and next computations are more transparent.

3. Study of the linearized operator

We start the study by an examination of the linearized problem, that we denote by
\[ L_c U = \mathcal{G} F, \] (4)
where
\[ U = (\eta, v), \quad F = (g, f), \]
\[ L_c U = \begin{pmatrix} \nabla \cdot v - \mathbf{c} \cdot \nabla \left( \eta - \frac{1}{6} \Delta \eta \right) \\ \nabla \eta - \mathbf{c} \cdot \nabla \left( v - \frac{1}{6} \Delta v \right) \end{pmatrix}, \]
\[ \mathcal{G} F = (\nabla \cdot f, \nabla g). \]
It is clear that if \( U = (\eta, v) \) is such that \( \text{curl}(v) = 0 \), then \( L_c U \) possesses the same property. Moreover, for any \( F = (g, f) \), the vector \( \mathcal{G} F \) possesses the curl free property for its two last components.

The vector function \( f \) and scalar function \( g \) are periodic with Fourier series
\[ f(x, t) = \sum_{k \in \Gamma'} f_k e^{ik \cdot x}, \]
\[ g(x, t) = \sum_{k \in \Gamma'} g_k e^{ik \cdot x}, \]
and we look for periodic solutions \( (\eta, v) \) such that \( \text{curl}(v) = 0 \), with the Fourier series
\[ \eta(x, t) = \sum_{k \in \Gamma'} \eta_k e^{ik \cdot x}, \]
\[ v(x, t) = \sum_{k \in \Gamma'} v_k e^{ik \cdot x}, \]
where \( \Gamma' \) is a lattice of the plane defined by two vectors \( K_1, K_2 \), and
\[ k \in \Gamma': \ k = (k_1, k_2) = n_1 K_1 + n_2 K_2, \quad n_1, n_2 \in \mathbb{Z}. \] (5)
We assume later that the two vectors \( K_1 \) and \( K_2 \) are symmetric with respect to the \( x_1 \) axis, making an angle \( \pm \theta \) with this axis which will be the direction of \( \mathbf{c} \). Then we get for \( k \in \Gamma' \)
\[-\left(1 + \frac{1}{6}|\mathbf{k}|^2\right)(\mathbf{c} \cdot \mathbf{k})\eta_{\mathbf{k}} + \mathbf{k} \cdot \mathbf{v}_{\mathbf{k}} = \mathbf{k} \cdot \mathbf{f}_{\mathbf{k}},\]

\[\mathbf{k} \eta_{\mathbf{k}} - \left(1 + \frac{1}{6}|\mathbf{k}|^2\right)(\mathbf{c} \cdot \mathbf{k})\mathbf{v}_{\mathbf{k}} = \mathbf{k} \cdot \mathbf{f}_{\mathbf{k}}.\]

Let us define

\[\Delta(\mathbf{k}, \mathbf{c}) = \left(1 + \frac{1}{6}|\mathbf{k}|^2\right)(\mathbf{c} \cdot \mathbf{k})^2 - |\mathbf{k}|^2.\] (6)

The linearized operator has a nontrivial kernel if there exists a pair \((\mathbf{k}_0, \mathbf{c}_0)\) satisfying

\[\Delta(\mathbf{k}_0, \mathbf{c}_0) = 0,\] (7)

or if \((\mathbf{k}_0 \cdot \mathbf{c}_0) = 0\). We need to study the set of \(\mathbf{k}\) in the plane, satisfying \(\Delta(\mathbf{k}, \mathbf{c}) = 0\) for a given velocity \(\mathbf{c}\), to obtain the kernel of the linearized operator. The big restriction is that our vectors \(\mathbf{k}\) need to belong to the lattice \(\Gamma'\).

If \(\Delta \neq 0\) and \((\mathbf{k} \cdot \mathbf{c}) \neq 0\), we obtain

\[\eta_{\mathbf{k}} = -\left(1 + \frac{1}{6}|\mathbf{k}|^2\right)(\mathbf{c} \cdot \mathbf{k})(\mathbf{k} \cdot \mathbf{f}_{\mathbf{k}}) + |\mathbf{k}|^2 \mathbf{g}_{\mathbf{k}} \Delta(\mathbf{k}, \mathbf{c}),\] (8)

\[\mathbf{v}_{\mathbf{k}} = -\mathbf{k}\left(1 + \frac{1}{6}|\mathbf{k}|^2\right)(\mathbf{c} \cdot \mathbf{k})\mathbf{g}_{\mathbf{k}} + \mathbf{k} \cdot \mathbf{f}_{\mathbf{k}} \Delta(\mathbf{k}, \mathbf{c}),\] (9)

where we notice that

\[\text{curl} (\mathbf{v}_{\mathbf{k}} e^{i\mathbf{k} \cdot \mathbf{x}}) = 0,\]

while for \((\mathbf{k} \cdot \mathbf{c}) = 0\), we have, \(\mathbf{k} = (0, k_2)\) and for \(k_2 \neq 0\)

\[\eta_{\mathbf{k}} = \mathbf{g}_{\mathbf{k}},\]

\[(v_1)_{\mathbf{k}} = 0,\]

\[(v_2)_{\mathbf{k}} = (f_2)_{\mathbf{k}},\] (10)

where the value 0 of \((v_1)_{\mathbf{k}}\) is necessary for satisfying the condition \(\text{curl}(v_{\mathbf{k}} e^{i\mathbf{k} \cdot \mathbf{x}}) = 0\). We give below estimates for \((\eta_{\mathbf{k}}, \mathbf{v}_{\mathbf{k}})\) in terms of \((\mathbf{f}_{\mathbf{k}}, \mathbf{g}_{\mathbf{k}})\) in cases of \(\Delta(\mathbf{k}, \mathbf{c}) \neq 0\). These estimates allow to give a bound of the pseudo-inverse of the linearized operator on its range.

We first study the set of wave vectors \(\mathbf{k}\) such that \(\Delta(\mathbf{k}, \mathbf{c}) = 0\). Assume \(\mathbf{c} = (c, 0)\), and let \(\mathbf{k} = (k_1, k_2) = n_1 \mathbf{K}_1 + n_2 \mathbf{K}_2\) satisfies \(\Delta(\mathbf{k}, \mathbf{c}) = 0\), where

\[\mathbf{K}_1 = k(1, \tau), \quad \mathbf{K}_2 = k(1, -\tau),\]

\[k > 0, \quad c > 0\]

which means that \(\tau = \tan \theta, \pm \theta\) being the angles between the axis \(x_1\) and the wave vectors \(\mathbf{K}_1, \) and \(\mathbf{K}_2\). We then have

\[k_1 = m_1 k, \quad k_2 = m_2 \tau k,\]

\[m_1 = n_1 + n_2\]

\[m_2 = n_1 - n_2,\]

and we observe that \(m_1\) and \(m_2\) have the same parity. Replacing in the equation \(\Delta(\mathbf{k}, \mathbf{c}) = 0\) we obtain

\[(m_1 c)^2 \left[1 + \frac{k^2}{6}(m_1^2 + \tau^2 m_2^2)\right]^2 = m_1^2 + \tau^2 m_2^2.\] (11)

We observe for a given \((c, k, \tau)\) that for any solution \((m_1, m_2)\) of (11) this corresponds in fact to the 4 solutions \((\pm m_1, \pm m_2)\).
Let \((c, k, \tau) = (c_0, k, \tau)\) be such that we have a solution \((m_1, m_2) = (1, 1)\) of (11). This means that

\[ c_0^2 \left\{ \frac{1 + k^2}{6} (1 + \tau^2) \right\}^2 = 1 + \tau^2. \]

First observe that for \(m_1 = 0\), Eq. (11) cannot be satisfied for \(m_2 \neq 0\). Now for \(m_1 \neq 0\), Eq. (11) can only have a finite number of solutions, since for any solution \((m_1, m_2)\) we have (study the maximum of the function \(x/(1 + (k^2/6)x)^2\) for \(x \in (0, \infty)\))

\[ m_1^2 \leq \frac{6}{4c_0^2 k^2}, \]

and when \(m_1\) is fixed, the quantity \(m_1^2 + \tau^2 m_2^2\) is the root of a second degree polynomial, with the additional condition for \(m_2\) to be an integer.

It is then clear that in general \((m_1, m_2) = (1, 1)\) is the only solution in \(\mathbb{N}^2\) of (11). Consider now six examples of such choices for \((c_0, k, \tau)\). Indeed, let us choose \(k = \frac{1}{2}\), which corresponds to fix the wave length in \(x_1\) as \(4\pi\) (this is large with respect to 1, which is one condition to respect for the model system (1) to be valid. Then we have

\[ c_0^2 = \frac{1 + \tau^2}{(1 + \frac{1}{24}(1 + \tau^2))^2} \leq 6 \]

where \(\tau = \tan \theta \in (0, +\infty)\). Let consider the following typical cases:

(i) \(\tau = 1/10, c_0 = \frac{240\sqrt{10}}{2501} (\theta = 5.71^\circ)\),

(ii) \(\tau = 2 - \sqrt{3}, c_0 = \frac{6\sqrt{\pi}}{50}(7\sqrt{3} - 5) (\theta = \pi/12 = 15^\circ)\),

(iii) \(\tau = 1/\sqrt{3}, c_0 = \frac{12\sqrt{3}}{9} (\theta = \pi/6 = 30^\circ)\),

(iv) \(\tau^2 = 1, c_0 = \frac{12\sqrt{3}}{9} (\theta = \pi/4 = 45^\circ)\),

(v) \(\tau^2 = 3, c_0 = \frac{12}{7} (\theta = \pi/3 = 60^\circ)\),

(vi) \(\tau = 3, c_0 = \frac{12\sqrt{10}}{17} (\theta = 71.6^\circ)\).

It is easy, to show, using (12) and the expression (11) for \(m_1 = 1\) and 2, that the solution \((m_1, m_2) = (1, 1)\) is the only solution in \(\mathbb{N}^2\) of (11) for all the above particular cases.

Assuming more generally that \((c_0, k, \tau)\) is in the situation where \((m_1, m_2) = (1, 1)\) is the only solution in \(\mathbb{N}^2\) of (11), we see that for \(m_1 \neq 0\), and \(|m_1| + |m_2| > M\), we have the following minoration of \(\Delta\):

\[ |\Delta| > C_1 m_1^2 (m_1^2 + \tau^2 m_2^2)^2, \]

where \(C_1\) is independent of \((m_1, m_2)\), which, in using the inequality

\[ |m_1| + |m_2| \leq (2 + \tau^{-2})^{1/2} (m_1^2 + \tau^2 m_2^2)^{1/2} \]

leads to

\[ |\eta_k| + ||v_k|| < C_2 \frac{|g_k| + ||f_k||}{m_1(|m_1| + |m_2|)}, \]

with \(C_2\) independent of \((m_1, m_2)\). Moreover, we have by hypothesis for \((m_1, m_2) \neq (0, 0)\) and \((\pm 1, \pm 1)\), \(|m_1| + |m_2| \leq M, m_1 \neq 0\),

\[ |\eta_k| + ||v_k|| < C_3 (|g_k| + ||f_k||). \]

Finally, for \(m_1 = 0\), we choose to take \((v_1)_k = 0\) (see (10)), and the above estimate is trivially satisfied.

We conclude that for \((m_1, m_2) \neq (0, 0)\) and \((\pm 1, \pm 1)\), and for our choice of determination of \(v_1\) in the case when \(m_1 = 0\),

\[ |\eta_k| + ||v_k|| < C(|g_k| + ||f_k||). \]
It remains to study the case when \((m_1, m_2) = (0, 0)\) or \((\pm 1, \pm 1)\).

For \((m_1, m_2) = (0, 0)\) we find easily that \(\eta_0 \text{ and } \nu_0 \text{ are arbitrary, hence giving a subspace of dimension 3 (this subspace has indeed a one-dimensional intersection with the part of the kernel given for } m_1 = 0)\).

For \((m_1, m_2) = (\pm 1, \pm 1)\), i.e. for \(k = (\pm 1, \pm \tau)\), we have for \((g, f)\) the compatibility condition under the form

\[
|k|g_k + \text{sgn}(m_1)k \cdot f_k = 0
\]

(13)
i.e. for instance, for \(k = (1, \tau)\), i.e. \((m_1, m_2) = (1, 1)\), and denoting below \(g_k\) by \(g_{1,1}\) in such a case

\[
\frac{1}{\sqrt{1 + \tau^2}} g_{1,1} + (f_1)_{1,1} + \tau (f_2)_{1,1} = 0.
\]

When the condition (13) is realized, then

\[
\eta_k = g_k + \beta \sqrt{1 + \tau^2},
\]

\[
\nu_k = \beta (1 + \tau \text{sgn}(m_1) \text{sgn}(m_2)),
\]

where \(\beta\) is arbitrary in \(\mathbb{C}\). For \(k = k(m_1, \tau m_2)\), where \((m_1, m_2) = (\pm 1, \pm 1)\), let us define the eigenvectors \(\xi_k\) by

\[
\xi_k = (\sqrt{1 + \tau^2}, 1, \tau \text{sgn}(m_1) \text{sgn}(m_2)) e^{ik(m_1 x_1 + \tau m_2 x_2)},
\]

then we have by construction

\[
\mathcal{L}_\nu \xi_k = 0.
\]

Now defining the Sobolev space

\[
H^l_{\nu_0} = \left\{ u = \sum_{k \in \ell^0} u_k e^{ikx} \in H^l \left\{ \left( \mathbb{R}/(2\pi/k)\mathbb{Z} \right) \times \left( \mathbb{R}/(2\pi/k\tau)\mathbb{Z} \right) \right\} : \right. \left. \text{where } k = k(m_1, \tau m_2), m_1, m_2 \in \mathbb{Z}, m_1 \text{ and } m_2 \text{ have same parity} \right\}
\]

The condition on the parities of \(m_1\) and \(m_2\) comes from the construction (recall that \(m_1 = n_1 + n_2, m_2 = n_1 - n_2\)). This leads to the invariance under the shift

\[
\sigma : (x_1, x_2) \mapsto \left( x_1 + \frac{\pi}{k}, x_2 + \frac{\pi}{k\tau} \right).
\]

Now with the Hermitian scalar product in \(\{H^0_{\nu_0}\}^3\), the compatibility condition (13) reads

\[
\langle F, \xi_k \rangle = 0, \quad k = k(\pm 1, \pm \tau).
\]

(14)

The above calculations mean that we are able to define a bounded operator \(T\) acting in \(\{H^p_{\nu_0}\}^3 \cap \{\text{curl}(\nu) = 0\}\), for any \(p \geq 0\), solving (4), provided the compatibility condition (13) is satisfied, and such that

\[
U = TF,
\]

\[
TF_k = U_k = (\eta_k, \nu_k),
\]

is given by (8), (9) for \(\Delta \neq 0\) and \((k \cdot c) \neq 0\), i.e. for \(k \neq k(\pm 1, \pm \tau)\), and for \(k_1 = km_1 \neq 0\). For \(k_1 = 0, k_2 \neq 0\)

\[
TF_k = (g_k, 0, (f_2)_k),
\]

and for \(k = (0, 0)\)

\[
TF_0 = 0,
\]

while for \(k = k(\pm 1, \pm \tau)\) we set

\[
TF_k = (g_k, 0).
\]

Notice that the operator \(T\) is defined here, even for \(F = (g, f)\) not satisfying the compatibility condition (14).

Since we restrict our attention to solutions symmetric with respect to the axis \(x_1\) of propagation, let us introduce the new spaces

\[
H_{\nu_0}^{1,e} = \{ w \in H^1_{\nu_0} : w \text{ is even in } x_2 \}.
\]
and similarly $H_{a_0}^{l,o} = \{w \in H_{a_0}^l, w \text{ is odd in } x_2\}$. Then, the above linear operator $T$ acts from $E_p = (H_{a_0}^{p,e})^2 \times (H_{a_0}^{p,o})^2$ into

$$G_p = (H_{a_0}^{p,e})^2 \times (H_{a_0}^{p,o}) \cap \{\text{curl}(v) = 0\},$$

and (2) can be understood in this space for $p \geq 2$ (this restriction is for having the nonlinear terms $(v^2, \eta v) \in (H_{a_0}^{p,e})^2 \times (H_{a_0}^{p,o})$). In the following we use the following notations:

$$\xi_0 = \frac{1}{2}(\xi_{(1,1)} + \xi_{(1,-1)}),$$
$$\xi_0^* = \frac{1}{2}(\xi_{(-1,1)} + \xi_{(-1,-1)}),$$

i.e.

$$\xi_0 = e^{ikx_1}(\sqrt{1 + \tau^2} \cos k\tau x_2, \cos k\tau x_2, i\tau \cos k\tau x_2),$$

and $\xi_0 \in G_p$ for any $p$. Notice that any $F \in E_p, \ p > 0$, has a Fourier expansion of the form

$$F = \sum_{m \in \mathbb{Z} \times \mathbb{N}_0} F_m e^{ikm_1x_1},$$

$$F_m = (s_m \cos k\tau m_2 x_2, (f_1)_m \cos k\tau m_2 x_2, (f_2)_m \sin k\tau m_2 x_2),$$

where $m_1$ and $m_2$ have the same parity in the sum, and $\mathbb{N}_0 = \mathbb{N} \cup \{0\}$. It then results for instance that the 4 components of the compatibility condition (14) reduces to the two conditions

$$\langle F, \xi_0 \rangle = 0, \quad \langle F, \xi_0^* \rangle = 0.$$

Now, let us introduce the O(2) group invariance, corresponding to the invariance of the system under shifts in $x_1$ and reflection $x_1 \mapsto -x_1$. The operator representing the shift is $\tau_a$ defined by

$$(\tau_a U)(x_1, x_2) = U(x_1 + a, x_2),$$

and the symmetry operator $S$ is defined by

$$SU(x_1, x_2) = (\eta(-x_1, x_2), \psi_1(-x_1, x_2), -\psi_2(-x_1, x_2)).$$

It is then clear that the O(2) symmetry is satisfied since

$$\tau_{2\pi/k} = I, \quad S\tau_a = \tau_{-a}S$$

and the systems (2) and (4) commute with $S$ and with $\tau_a$, for any $a$ real. Then, we can assert the following

**Theorem 1.** Assume that $(c_0, k, \tau)$ is such that $(m_1, m_2) = (1, 1)$ is the only solution in $\mathbb{N}^2$ of (11). Then, for any given

$$F = (g, f) \in E_p = (H_{a_0}^{p,e})^2 \times (H_{a_0}^{p,o}), \quad p \geq 0,$$

such that the following compatibility conditions

$$\langle F, \xi_0 \rangle = \langle F, \xi_0^* \rangle = 0$$

hold for the Fourier components with $k = k(\pm 1, \pm \tau)$, the general solution $U = (\eta, v) \in G_p$ of the system

$$L_{c_0} U = GF,$$

is given by

$$U = TF + A\xi_0 + \tilde{A}\xi_0^* + C\xi_0 + D\xi_1,$$

where

$$\xi_0 = (1, 0, 0), \quad \xi_1 = (0, 1, 0),$$
$$\xi_0^* = (\sqrt{1 + \tau^2} \cos k\tau x_2, \cos k\tau x_2, i\tau \sin k\tau x_2) e^{ikx_1},$$

and

$$\xi_1 = (\sqrt{1 + \tau^2} \cos k\tau x_2, \cos k\tau x_2, i\tau \sin k\tau x_2) e^{ikx_1}.$$
\( A \in \mathbb{C}, \ C, \ D \in \mathbb{R}, \) and \( T \) is the bounded linear operator defined above. Moreover, we have the symmetry properties

\[
STF = TSF, \quad \tau_a TF = T \tau_a F.
\]

\[
S\xi_0 = \tau_a \xi_0 = \xi_0, \quad S\xi_1 = \tau_a \xi_1 = \xi_1, \quad S\xi_0 = \bar{\xi}_0, \quad \tau_a \xi_0 = e^{ika} \bar{\xi}_0.
\]

**Remark.** The existence of eigenvectors \( \xi_1 \) and \( \xi_0 \) for the linear operator \( L_c \) comes from the important property of system (2) to possess the family of “trivial” solutions

\[
U^{(0)} = (C, D, 0) \quad (16)
\]

for arbitrary constants \( C, D \).

4. Bifurcating solutions

Let us set \( c = c_0/(1 + \mu) \), and rewrite the equation as

\[
L_{c_0} U + \mu \tilde{G} U + (1 + \mu) \tilde{G} B(U, U) = 0, \quad (17)
\]

where

\[
B(U, U) = \left( \frac{1}{2} |v|^2, \eta v \right).
\]

Then we decompose \( U \in G_p \) as

\[
U = A\xi_0 + \bar{A}\xi_0 + C\xi_0 + D\xi_1 + V,
\]

where \( V \) has the same properties as \( TF \) above, i.e.

\[
V_0 = 0,
\]

for \( k = k(\pm 1, \pm \tau) \)

\[
V_k = (\eta_k, 0), \quad \text{for} \quad k_1 = 0, k_2 \neq 0
\]

\[
V_k = (\eta_k, 0, (\eta_2)k).
\]

Notice that with our definition of \( V \), we have

\[
\langle V, \xi_1 \rangle = \langle V, \xi_0 \rangle = 0,
\]

\[
\langle V, \xi_0 \rangle = \sqrt{1 + \tau^2} \frac{4\pi^2}{k^2 \tau} \eta_{1,1}.
\]

Replacing the expression for \( U \) in the nonlinear equation (17), the unknown are \( V, A, C, D \) in function of the parameter \( \mu \). The form of (17) implies, from Theorem 1, that we can rewrite Eq. (17) as

\[
V + \mu T U + (1 + \mu) T B(U, U) = 0, \quad (18)
\]

\[
\mu A(\xi_0, \bar{\xi}_0) + \mu \langle V, \xi_0 \rangle + (1 + \mu) \langle B(U, U), \xi_0 \rangle = 0, \quad (19)
\]

where the second equation (compatibility condition) is in \( \mathbb{C} \), the writing of the complex conjugate equation of (19) being useless. Notice that the first equation may be solved by the implicit function theorem in \( G_p \) with respect to \( V \), and that by construction we have

\[
T \xi_0 = T \xi_1 = 0, 
\]

\[
T \xi_0 = (\sqrt{1 + \tau^2} \cos k \tau x_2 e^{ika}, 0).
\]
It then results that for $A, C, D, \mu$, close enough to 0, we obtain
\[ V = \mathcal{V}(A, \tilde{A}, C, D, \mu) \in G_p \]
and, because of the $O(2)$ invariance and the uniqueness of $\mathcal{V}$, the following property holds:
\[ \tau_{\alpha} \mathcal{V}(A, \tilde{A}, C, D, \mu) = \mathcal{V}(A e^{i k a}, \tilde{A} e^{-i k a}, C, D, \mu), \]
\[ S \mathcal{V}(A, \tilde{A}, C, D, \mu) = \mathcal{V}(\bar{A}, A, C, D, \mu). \]

A consequence of these symmetry properties is that if $A \equiv 0$, then $\mathcal{V}$ and $X$ are invariant under shifts $\tau_{\alpha}$, which means that $U$ is independent of $x_1$. It then results, because of the parity in $x_2$ that $U = U^{(0)}$ lies in the family of “trivial solutions” mentioned above. A careful examination of the principal part of $\mathcal{V}$ shows that
\[ \mathcal{V}(A, \tilde{A}, C, D, \mu) = -\mu A T \xi_0 - \mu \tilde{A} T \bar{\xi}_0 - T B(X, X) + O(\|\mu\| X^2 + \|X\|^3), \]
where
\[
X = A \xi_0 + \tilde{A} \bar{\xi}_0 + C \zeta_0 + D \xi_1,
\]
\[
B(X, X) = \begin{pmatrix}
\frac{1}{2} D^2 + D \cos k \tau x_2 (A e^{i k x_1} + \tilde{A} e^{-i k x_1}) \\
+ (\frac{A^2}{4} e^{2i k x_1} + \frac{\tilde{A}^2}{4} e^{-2i k x_1})(1 - \tau^2 + (1 + \tau^2) \cos 2k \tau x_2) \\
+ (\frac{|A|^2}{2} (1 + \tau^2 + (1 - \tau^2) \cos 2k \tau x_2)
\end{pmatrix}
\]
\[
CD + (C + D \sqrt{1 + \tau^2}) \cos k \tau x_2 (A e^{i k x_1} + \tilde{A} e^{-i k x_1})
+ |A|^2 \sqrt{1 + \tau^2} \sin 2k \tau x_2
\]
\[
|A|^2 \sqrt{1 + \tau^2} \sin 2k \tau x_2 (A^2 e^{2i k x_1} - \tilde{A}^2 e^{-2i k x_1})
\]
With simple, but tedious computations, and by denoting
\[ U = X - V_1 - V_2 + O(\|\mu\| X^2 + \|X\|^3), \]
where
\[
V_1 = \mu A T \xi_0 + \mu \tilde{A} T \bar{\xi}_0,
\]
\[ V_2 = T B(X, X), \]
we obtain
\[
V_1 = \mu \sqrt{1 + \tau^2} (A e^{i k x_1} + \tilde{A} e^{-i k x_1}) \cos (k \tau x_2)(1, 0, 0),
\]
\[
V_2 = |A|^2 \xi_2 + \xi_3 D (A e^{i k x_1} + \tilde{A} e^{-i k x_1}) + (A^2 e^{2i k x_1} + \tilde{A}^2 e^{-2i k x_1}) \xi_1 + A^2 e^{2i k x_1} \xi_2 + \tilde{A}^2 e^{-2i k x_1} \bar{\xi}_2,
\]
where
\[
\xi_2 = \left( \frac{1}{2} (1 - \tau^2) \cos 2k \tau x_2, 0, 0 \right),
\]
\[
\xi_3 = (\cos k \tau x_2, 0, 0),
\]
\[
\xi_1 = (c_1, c_2, 0),
\]
\[
\xi_2 = (d_1 \cos 2k \tau x_2, d_2 \cos 2k \tau x_2, \tilde{c} d_2 \cos 2k \tau x_2),
\]
\[
c_1 = \frac{2(1 + \frac{3}{2} k^2) c_0 \sqrt{1 + \tau^4} + 1 - \tau^2}{4 - 4(1 + \frac{3}{2} k^2)^2 c_0^2},
\]
\[
c_2 = \frac{(1 + \frac{3}{2} k^2) c_0 (1 - \tau^2) + 2 \sqrt{1 + \tau^2}}{4 - 4(1 + \frac{3}{2} k^2)^2 c_0^2},
\]
\[
d_1 = \frac{\{c_0\sqrt{1 + \tau^2}(1 + \frac{2}{3}k^2(1 + \tau^2)) + \frac{1}{4}(1 + \tau^2)\}(1 + \tau^2)}{2(1 + \tau^2) - 2c_0^2(1 + \frac{2}{3}k^2(1 + \tau^2))^2},
\]
\[
d_2 = \frac{\{\frac{\sqrt{2}}{2}(1 + \frac{2}{3}k^2(1 + \tau^2)) + \sqrt{1 + \tau^2}(1 + \tau^2)\}}{2(1 + \tau^2) - 2c_0^2(1 + \frac{2}{3}k^2(1 + \tau^2))^2}.
\]

Now replacing \( V \) by \( \mathcal{V} \) in (19), we obtain one equation in \( \mathbb{C} \) of the form

\[ h(A, \tilde{A}, C, D, \mu) = 0 \]  

(21)
such that

\[ h(A e^{ika}, \tilde{A} e^{-ika}, C, D, \mu) = e^{ika} h(A, \tilde{A}, C, D, \mu), \]
\[ h(A, \tilde{A}, C, D, \mu) = \bar{h}(\tilde{A}, A, C, D, \mu) \]

holds for any real \( a \), because of the \( O(2) \) equivariance of the system (18), (19). It results that \( h \) takes the following form where the function \( Q \) is real valued

\[ h(A, \tilde{A}, C, D, \mu) = A Q(\vert A \vert^2, C, D, \mu). \]  

(22)

We observe that \( 2B(U_1, U_2) = (v_1 \cdot v_2, \eta_1 v_2 + \eta_2 v_1) \) and

\[ \{B(X, X), \xi_0\} = \frac{2\pi^2}{k^2\tau}\{2\sqrt{1 + \tau^2} D + (1 + \tau^2) C\} A, \]
\[ \mu\{\mathcal{V}, \xi_0\} = -\frac{2\pi^2}{k^2\tau}\sqrt{1 + \tau^2}\{\mu^2\sqrt{1 + \tau^2} + \mu D\} A + O(\mu^2 \|X\|^2 + |\mu||X||^3), \]
\[ \{2B(A \xi_0, -\vert A \vert^2 \xi_2), \xi_0\} = -\frac{2\pi^2}{k^2\tau} \vert A \vert^2 \frac{1}{4} (1 - \tau^2)^2, \]
\[ \{2B(\tilde{A} \xi_0, -A^2 e^{2ik_1 \xi_1}), \xi_0\} = -\frac{2\pi^2}{k^2\tau} \vert A \vert^2 \{2\sqrt{1 + \tau^2} c_2 + (1 - \tau^2) c_1\}, \]
\[ \{2B(\tilde{A} \xi_0, -A^2 e^{2ik_1 \xi_2}), \xi_0\} = -\frac{2\pi^2}{k^2\tau} \vert A \vert^2 \left\{ \frac{1 + \tau^2}{2} d_2 + \frac{1 + \tau^2}{2} d_1 \right\}, \]

hence

\[ Q = 2\mu(1 + \tau^2) + 2\sqrt{1 + \tau^2} D + (1 + \tau^2) C \]
\[ - \vert A \vert^2 \left\{ 2\sqrt{1 + \tau^2} c_2 + (1 - \tau^2) c_1 + \frac{1}{4} (1 - \tau^2)^2 + (1 + \tau^2)^{3/2} d_2 + \frac{1 + \tau^2}{2} d_1 \right\} \]
\[ + O\{(|\mu| + |C| + |D| + |A|^2)^2\}. \]

An easy consequence is that \( A = 0 \) is a solution of our problem. This corresponds to \( X = C \xi_0 + D \xi_1 \), and finally to the family (16) of trivial solutions \( U(0) \).

Nontrivial solutions are given by the solutions of the real equation

\[ Q(\vert A \vert^2, C, D, \mu) = 0. \]  

(23)

At principal order this leads to

\[ \vert A \vert^2 = -\frac{1}{d} \{2\mu(1 + \tau^2) + 2\sqrt{1 + \tau^2} D + (1 + \tau^2) C\} + O\{(|\mu| + |C| + |D|)^2\}, \]

where

\[ d = 2\sqrt{1 + \tau^2} c_2 + (1 - \tau^2) c_1 + \frac{1}{4} (1 - \tau^2)^2 + (1 + \tau^2)^{3/2} d_2 + \frac{1 + \tau^2}{2} d_1 \]  

(24)

provided that \( d \neq 0 \). Indeed \( d \) is a nonconstant meromorphic function of \( \tau \) in a neighborhood of the positive real axis, hence it may cancel only for a discrete set of isolated values of \( \tau \in (0, \infty) \). Finally we proved the following
Theorem 2. Assume that \((c_0, k, \tau)\) is such that \((m_1, m_2) = (1, 1)\) is the only solution in \(\mathbb{N}^2\) of (11), then for any \(p \geq 2\), there is a neighborhood of \((c_0, 0, 0)\) in \(\mathbb{R}^3\) such that the bifurcation surface for \((c_b, C, D)\), where \(c_b\) is the critical velocity of the travelling wave, \(C\) and \(D\) are respectively the averages of the elevation \(\eta\) and of the horizontal velocity along the wave, is analytic and satisfies
\[
\frac{c_b}{c_0} = 1 + \frac{D}{\sqrt{1 + \tau^2}} + \frac{C}{2} + O\left(\left|\frac{(C) + |D|}{2}\right|^2\right).
\]
The bifurcation of travelling waves of the form \(U = (\eta, v) \in G_p\) takes place for \(c > c_b\) if the coefficient \(d\) defined in (24) is < 0, and for \(c < c_b\) if \(d > 0\), the amplitude is such that \(|A|^2\) is analytic in \((c - c_b, C, D)\), satisfying
\[
|A|^2 = (c_b - c)\left\{\frac{2(1 + \tau^2)}{c_0d} + O\left(\left|\frac{c_b - c}{|C| + |D|}\right|^3\right)\right\}.
\]
Moreover
\[
U = A\xi_0 + A\xi_0 + C\xi_0 + D\xi_1 + \mathcal{V}(A, \tilde{A}, C, D, \mu),
\]
where \(\mu = \frac{c_0}{c} - 1\), and a phase shift \(\phi\) on \(A\) corresponds to a translation \(\phi/k\) for \(x_1\).

Corollary 3. With the assumptions of the theorem above, the form of the free surface, even in \(x_1\), and with \(C = D = 0\), is given at leading order by
\[
\eta = \varepsilon \cos kx_1 \cos k\tau x_2 - \frac{\varepsilon^2}{2(1 + \tau^2)} \left\{\frac{1 - \tau^2}{4} \cos 2k\tau x_2 + c_1 \cos 2kx_1 + d_1 \cos 2kx_1 \cos 2k\tau x_2\right\} + O(\varepsilon^3)
\]
where \(\varepsilon = 2|A|\sqrt{1 + \tau^2}\). For \(\tau\) close to 0, we have
\[
\eta \approx \varepsilon \cos kx_1 \cos k\tau x_2 - \varepsilon^2 \left\{\frac{1}{8} \cos 2k\tau x_2 + c_1^{(0)} \cos 2kx_1 (1 + \cos 2k\tau x_2)\right\} + O(\varepsilon^3)
\]
with
\[
c_1^{(0)} = \frac{1 + 2c_1^{(0)}(1 + \frac{2}{3}k^2)}{4 - 4(c_0^{(0)})^2(1 + \frac{2}{3}k^2)^2}, \quad c_0^{(0)} = \frac{1}{1 + k^2/6},
\]
and
\[
\varepsilon^2 \approx \frac{8(c_b - c)}{c_0^{(0)}d^{(0)}},
\]
\[
d^{(0)} = \frac{6c_0^{(0)}(1 + \frac{2}{3}k^2) + 15/2}{4 - 4(c_0^{(0)})^2(1 + \frac{2}{3}k^2)^2} + \frac{1}{4} < 0 \quad \text{for } k \text{ small enough.}
\]

Remark 1. We notice that for \(\tau\) close to 0, there are “nodal lines” given by \(x_2 = \pi/2k\tau\) modulo(\(\pi/k\tau\)), since, up to order \(\varepsilon^2\) included, we have \(\eta \approx \varepsilon^2/8\) which is independent of \(x_1\).

Remark 2. It is observed experimentally in [12] that for moderate values of \(\varepsilon\) it appears a local maximum in the troughs (between two strong minima). This is an effect easily explained with the influence of order \(\varepsilon^2\) terms. The occurrence of local minima between two strong maxima, can be explained with the presence of order \(\varepsilon^3\) terms.

The function \(\eta(x_1, x_2)\) is computed numerically for the six special cases mentioned earlier. The corresponding angle between the basic wave vectors \(2\theta\) range from 11.4° to 143°. For fitting with the domain of validity of model equations (1), namely the small-amplitude (i.e. the ratio between the amplitude of the wave and the average water depth is small) and long wavelength (i.e. the product of the typical wave number and the average water depth is small) requirements, we take \(k = \frac{1}{2}\) and \(\varepsilon = 0.2\) in our computation, recalling that the water depth is scaled to 1 in our model. The transport velocity \(c = c_0(1 - d\varepsilon^2/8(1 + \tau^2)^2)\) + higher order terms.
In Fig. 1, we take $\tau = 1/10$ which is in the KP range (i.e. wave surfaces are weakly two-dimensional, or equivalently $\tau^2 \ll 1$). The surface profile $\eta(x_1, x_2)$ is plotted on the left and the surface profiles at $x_2 = 0$ (solid line) and at $x_2 = L_{x_2}/4 = \pi/(2k\tau)$ (dashed line) are plotted on the right. We first note that the surface seems to comprise of rectangular cells, with nodal lines at $x_2 = L_{x_2}/4 = \pi/(2k\tau)$ (see the dashed line on the right), which is a phenomenon linked with deep water experiments [12]. Furthermore, there is a local maximum in the trough region (as observed in [12]).

In Fig. 2, we take $\tau = 2 - \sqrt{3}$ which is still in the KP range. The surface profiles $\eta(x_1, x_2)$ is plotted on the left and the surface profiles at $x_1 = 0$ (solid line) and at $x_1 = L_{x_1}/4 = \pi/(2k\tau)$ (dashed line) are plotted on the right. The
The surface clearly comprises hexagonal cells with no nodal lines. In the \(x_2\) direction, the crest is narrower than the valley (see the solid line). This figure looks qualitatively like Fig. 7(b) of [3].

The surface profiles for \(\tau = 1/\sqrt{3}\) and \(\tau = 1\) are plotted in Fig. 3. Since our model does not require the wave to be weakly two-dimensional, it does not require \(\tau\) to be small as for the KP equation. For \(\tau = 1/\sqrt{3}\) the figure shows hexagonal cells (as for experiments in shallow water: see Fig. 1a of [11]), while for \(\tau = 1\) there are square cells. However, the solution has not such symmetries. In the latter case, the invariance under a rotation by \(\pi/2\) is broken at the \((\varepsilon^2)\) order.

On Fig. 4 we plot surface profiles for \(\tau = \sqrt{3}\) and \(\tau = 3\). The last surface resembles the surface in Fig. 2 rotated by 90°.

References