



The Whitham Equation as a model for surface water waves



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HIGHLIGHTS

- Definition of Whitham scaling regime.
- Derivation of a Hamiltonian Whitham system.
- Asymptotic derivation of the Whitham equation.
- Comparison of Whitham, KdV, BBM and Padé models with inviscid free surface dynamics.

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ABSTRACT

The Whitham equation was proposed as an alternate model equation for the simplified description of uni-directional wave motion at the surface of an inviscid fluid. As the Whitham equation incorporates the full linear dispersion relation of the water wave problem, it is thought to provide a more faithful description of shorter waves of small amplitude than traditional long wave models such as the KdV equation.

In this work, we identify a scaling regime in which the Whitham equation can be derived from the Hamiltonian theory of surface water waves. A Hamiltonian system of Whitham type allowing for two-way wave propagation is also derived. The Whitham equation is integrated numerically, and it is shown that the equation gives a close approximation of inviscid free surface dynamics as described by the Euler equations. The performance of the Whitham equation as a model for free surface dynamics is also compared to different free surface models: the KdV equation, the BBM equation, and the Padé (2,2) model. It is found that in a wide parameter range of amplitudes and wavelengths, the Whitham equation performs on par with or better than the three considered models.

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1. Introduction

In its simplest form, the water-wave problem concerns the flow of an incompressible inviscid fluid with a free surface over a horizontal impenetrable bed. In this situation, the fluid flow is described by the Euler equations with appropriate boundary conditions, and the dynamics of the free surface are of particular interest in the solution of this problem.

There are a number of model equations which allow the approximate description of the evolution of the free surface without having to provide a complete solution of the fluid flow below the surface. In the present contribution, interest is focused

on the derivation and evaluation of a nonlocal water-wave model known as the Whitham equation. The equation is written as

$$\eta_t + \frac{3}{2} \frac{c_0}{h_0} \eta \eta_x + K_{h_0} * \eta_x = 0, \quad (1)$$

where the convolution kernel K_{h_0} is given in terms of the Fourier transform by

$$\mathcal{F}K_{h_0}(\xi) = \sqrt{\frac{g \tanh(h_0 \xi)}{\xi}}, \quad (2)$$

g is the gravitational acceleration, h_0 is the undisturbed depth of the fluid, and $c_0 = \sqrt{gh_0}$ is the corresponding long-wave speed. The convolution can be thought of as a Fourier multiplier operator, and (2) represents the Fourier symbol of the operator.

The Whitham equation was proposed by Whitham [1] as an alternative to the well known Korteweg–de Vries (KdV) equation

$$\eta_t + c_0 \eta_x + \frac{3}{2} \frac{c_0}{h_0} \eta \eta_x + \frac{1}{6} c_0 h_0^2 \eta_{xxx} = 0. \quad (3)$$

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The validity of the KdV equation as a model for surface water waves can be described as follows. Suppose a wave field with a prominent amplitude a and characteristic wavelength l is to be studied. The KdV equation is known to produce a good approximation of the evolution of the waves if the amplitude of the waves is small and the wavelength is large when compared to the undisturbed depth, and if in addition, the two non-dimensional quantities a/h_0 and h_0^2/l^2 are of similar size. The latter requirement can be written in terms of the Stokes number as

$$\delta = \frac{al^2}{h_0^3} \sim 1.$$

While the KdV equation is a good model for surface waves if $\delta \sim 1$, one notorious problem with the KdV equation is that it does not model accurately the dynamics of shorter waves. Recognizing this shortcoming of the KdV equation, Whitham proposed to use the same nonlinearity as the KdV equation, but couple it with a linear term which mimics the linear dispersion relation of the full water-wave problem. Thus, at least in theory, the Whitham equation can be expected to yield a description of the dynamics of shorter waves which is closer to the solutions of the more fundamental Euler equations which govern the flow.

The Whitham equation has been studied from a number of vantage points during recent years. In particular, the existence of traveling and solitary waves has been established in [2,3]. Well posedness of a similar equation was investigated in [4–6], and a model with variable depth has been studied numerically in [7]. Moreover, it has been shown in [8,9] that periodic solutions of the Whitham equation feature modulational instability for short enough waves in a similar way as small-amplitude periodic wave solutions of the water-wave problem. However, even though the equation is routinely mentioned in texts on nonlinear waves [10, 11], it appears that the performance of the Whitham equation in the description of surface water waves has not been investigated so far.

The purpose of the present article is to give an asymptotic derivation of the Whitham equation as a model for surface water waves, and to confirm Whitham's expectation that the equation is a fair model for the description of time-dependent surface water waves. For the purpose of the derivation, we introduce an exponential scaling regime in which the Whitham equation can be derived asymptotically from an approximate Hamiltonian principle for surface water waves. In order to motivate the use of this scaling, note that the KdV equation has the property that wide classes of initial data decompose into a number of solitary waves and small-amplitude dispersive residue [12]. For the KdV equations, solitary-wave solutions are known in closed form, and are given by

$$\eta = \frac{a}{h_0} \operatorname{sech}^2 \left(\sqrt{\frac{3a}{4h_0^3}} (x - ct) \right) \quad (4)$$

for a certain wave celerity c . These waves clearly comply with the amplitude–wavelength relation $a/h_0 \sim h_0^2/l^2$ which was mentioned above. It appears that the Whitham equation – as indeed do many other nonlinear dispersive equations – also has the property that broad classes of initial data rapidly decompose into ordered trains of solitary waves (see Fig. 1). Quantifying the amplitude–wavelength relation for these solitary waves yields an asymptotic regime which is expected to be relevant to the validity of the Whitham equation as a water wave model.

As the curve fit in the right panel of Fig. 1 shows, the relationship between wavelength and amplitude of the Whitham solitary waves can be approximately described by the relation $\frac{a}{h_0} \sim e^{-\kappa(l/h_0)^\nu}$ for certain values of κ and ν . Since the Whitham solitary waves are not known in exact form, the values of κ and ν have to be found numerically. Then one may define a Whitham scaling regime

$$\mathcal{W}(\kappa, \nu) = \frac{a}{h_0} e^{\kappa(l/h_0)^\nu} \sim 1, \quad (5)$$

and it will be shown in Sections 2 and 3 that this scaling can be used advantageously in the derivation of the Whitham equation. The derivation proceeds by examining the Hamiltonian formulation of the water-wave problem due to Zakharov, Craig and Sulem [13,14], and by restricting to wave motion which is predominantly in the direction of increasing values of x . The approach is similar to the method of [15], but relies on the new relation (5).

First, in Section 2, a Whitham system is derived which allows for two-way propagation of waves. The Whitham equation is found in Section 3. Finally, in Section 4, a comparison of modeling properties of the KdV and Whitham equations is given. The comparison also includes the regularized long-wave equation

$$\eta_t + c_0 \eta_x + \frac{3}{2} \frac{c_0}{h_0} \eta \eta_x - \frac{1}{6} h_0^2 \eta_{xxt} = 0, \quad (6)$$

which was put forward in [16] and studied in depth in [17], and which is also known as the BBM or PBBM equation. The linearized dispersion relation of this equation is not an exact match to the dispersion relation of the full water-wave problem, but it is much closer than the KdV equation, and it might also be expected that this equation may be able to model shorter waves more successfully than the KdV equation. In order to obtain an even better match of the linear dispersion relation, one may make use of Padé expansions. In the context of simplified evolutions equations, this approach was pioneered in [18]. For uni-directional models, this approach was advocated in [19], and in particular, the equation based on the Padé (2,2) approximation was studied in depth. In dimensional variables, this model takes the form

$$\eta_t + c_0 \eta_x + \frac{3}{2} \frac{c_0}{h_0} \eta \eta_x - \frac{3}{20} c_0 h_0^2 \eta_{xxx} - \frac{19}{60} h_0^2 \eta_{xxt} = 0. \quad (7)$$

The dispersion relations for the KdV, BBM and Padé (2,2) models are respectively

$$c(k) = c_0 - \frac{1}{6} c_0 h_0^2 k^2 \quad (\text{KdV}),$$

$$c(k) = c_0 \frac{1}{1 + \frac{1}{6} h_0^2 k^2} \quad (\text{BBM}),$$

$$c(k) = c_0 \frac{1 + \frac{3}{20} h_0^2 k^2}{1 + \frac{19}{60} h_0^2 k^2} \quad (\text{Padé (2,2)}).$$

These approximate dispersion relations are compared to the full dispersion relation in Fig. 2. It appears clearly that the Padé (2,2) approximation remains much closer to the full dispersion relation than the dispersion relations based on either the linear KdV or linear BBM equations. As will be seen in Section 4, solutions of both the Whitham and Padé (2,2) equations give closer approximations to solutions of the full Euler equations than either the KdV or BBM equations in most cases investigated. However, the Whitham equation still keeps a slight edge over the Padé model.

2. Derivation of evolution systems of Whitham type

The surface water-wave problem is generally described by the Euler equations with slip conditions at the bottom, and kinematic and dynamic boundary conditions at the free surface. Assuming weak transverse effects, the unknowns are the surface elevation $\eta(x, t)$, the horizontal and vertical fluid velocities $u_1(x, z, t)$ and $u_2(x, z, t)$, respectively, and the pressure $P(x, z, t)$. If the assumption of irrotational flow is made, then a velocity potential $\phi(x, z, t)$ can be used. In order to nondimensionalize the problem, the undisturbed depth h_0 is taken as a unit of distance, and the

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