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A simplified method to estimate tidal current effects on the ocean wave power resource

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ABSTRACT

Although ocean wave power can be significantly modified by tidal currents, resource assessments at wave energy sites generally ignore this effect, mainly due to the difficulties and high computational cost of developing coupled wave-tide models. Furthermore, validating the prediction of wave-current interaction effects in a coupled model is a challenging task, due to the paucity of observational data. Here, as an alternative to fully coupled numerical models, we present a simplified analytical method, based on linear wave theory, to estimate the influence of tidal currents on the wave power resource. The method estimates the resulting increase (or decrease) in wave height and wavelength for opposing (or following) currents, as well as quantifying the change in wave power. The method is validated by applying it to two energetic locations around the UK shelf – Pentland Firth and Bristol Channel – where wave/current interactions are significant, and for which field data are available. Results demonstrate a good accuracy of the simplified analytical approach, which can thus be used as an efficient tool for making rapid estimates of tidal effects on the wave power resource. Additionally, the method can be used to help better interpret numerical model results, as well as observational data.

1. Introduction

The exploitation of ocean wave power as a renewable energy resource has generated much interest in academia and industry, and has inspired many inventors, with more than one thousand patents registered to date for wave energy technologies [1]. The accurate assessment of site-specific ocean wave resource is the first step in developing projects for wave energy extraction [2].

Wave-current interactions are routinely ignored in such resource assessments (e.g. Refs. [3,4]), despite earlier research that illustrates the significant influence of tidal currents on wave properties, such as height and wavelength [5–7]. This is partly due to the high computational cost associated with running coupled wave-tide models; also, validating wave-current interaction effects in numerical models is a challenging task due the paucity of observations and the complexity of the physical processes involved.

The effect of tidal currents on the wave power resource has been considered in a few studies to date, on the basis of coupled wave-tide models. Barbariol et al. [8] demonstrated that the inclusion of wave-current interaction (WCI) effects could yield up to a 30% difference in wave power estimates at a location in the Gulf of Venice. The ROMS (Regional Ocean Modelling System) ocean model and SWAN (Simulating WAve Nearshore) wave model were used in coupled mode to conduct this study. Using the same modelling approach, Hashemi and Neill [9] showed that tidal currents can alter wave power by more than 10% in some regions of the northwest European shelf seas. They also briefly discussed a simple method to calculate this effect. However, in their method, they only considered the effect of tides on the wave group velocity, but the effect on wave height, which might be greater, was ignored. Furthermore, due to this limitation, no comparison with observations was made – which could have assessed the accuracy of the method. Saruwatari et al. [10] used a coupled model (SWAN and MOHID Water Modelling System [11]) to study the effect of WCI on the wave power, around Orkney. They reported an up to 200% increase in wave height, when waves and currents are opposing. However, they did not demonstrate that their coupled model improved the wave simulation, in comparison to a decoupled SWAN model.

In this research, a simplified but adequately accurate and efficient analytical method is proposed to estimate the effect of tidal

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currents on the wave power resource. Wave power, in general, is proportional to the wave group velocity and the wave height squared (see Eq. (1)); hence, WCI effects on both properties are included in the method. A limitation is that the method assumes waves are either following or opposing the currents. This assumption is valid in the majority of laboratory studies [12] and also applies in the field to many wave energy sites [13].

2. Methods

2.1. Theoretical background

Both wave height – which quantifies the magnitude of wave energy – and group velocity – which is the speed of wave energy transport – are modified by tidal currents. Here, we present a simple analytical method, based on the linear wave theory, for estimating these changes as a function of the current velocity, when currents and waves are aligned (opposing or following). We will only consider deep water waves (or nearly), for which linear theory is a reasonable approximation. We will also assume that the current field is specified (i.e., the effect of waves on currents is neglected).

2.1.1. Wave power in the absence of tides

In water of depth h and in the absence of a current, the period-averaged energy flux per unit width of wave crest (i.e. the mean wave power P_o in W/m) is equal to the mean rate of work done by the dynamic pressure over a wave period.[1] According to linear wave theory, for a monochromatic wave of period T_o and height H_o, this is given by Ref. [14],

$$P_o = E_{fo} = E_o C_{go} = \left\{ \frac{1}{8} \rho g H_o^2 \right\} C_{go}; \quad C_{go} = \frac{\sigma_o}{k_o} \left\{ \frac{1}{2} \left(1 + \frac{2k_o h}{\sinh 2k_o h} \right) \right\} \tag{1}$$

where C_{go} is the group velocity, E_o is mean wave energy, $\sigma_o = 2\pi/T_o$ is the wave angular frequency, and $k_o = 2\pi/L_o$ is the wave number (with L_o the wavelength). The subscript o indicates that wave properties are evaluated *in the absence* of a background current. The angular frequency and wavenumber are related to water depth by the linear dispersion relationship,

$$\sigma_0^2 = g k_o \tanh(k_o h) \tag{2}$$

For deep water waves, i.e., $k_o h \geq \pi$ [14], $\tanh(k_o h) \simeq 1$ in Eq. (2) and $k_o \simeq \sigma_0^2/g$. Hence, in Eq. (1), we have $C_{go} \simeq g/(2\sigma_o) = gT_o/(4\pi)$, which leads to,

$$P_o = \frac{\rho g}{32\pi} H_o^2 T_o \tag{3}$$

For irregular waves described by a wave energy spectrum, with significant wave height H_{so} and wave energy period T_{eo}, H_o would be replaced in Eq. (3) by the root-mean-square (RMS) wave height $H_{o,RMS}$ (with, in deep water, $H_{o,RMS} = H_{so}/\sqrt{2}$) and T_o by an equivalent "energy" wave period T_{eo} (see Table 1 for the definition of the energy period based on a wave energy spectrum).

2.1.2. Wave power in the presence of tidal currents

When a monochromatic wave propagates in the presence of a tidal current of magnitude u (projected in the direction of wave propagation), the wave energy flux is no longer conserved, due to energy exchange between the wave and current fields. Instead, the total period-averaged energy flux (or transport) E_{tf} is conserved, which in a vertical plane comprises other terms such as the kinetic energy of the current,[2] and is given by (e.g. Refs. [15,16]),

$$E_{tf} = \underbrace{[E\, C_g]}_{(i)} + \underbrace{[E\, u]}_{(ii)} + \underbrace{\left[\frac{1}{2}\rho g h u^3\right]}_{(iii)} + \underbrace{\left[u\left(2\frac{C_g}{C} - \frac{1}{2}\right)E\right]}_{(iv)} = \text{cst} \tag{4}$$

where each term on the right-hand-side is interpreted as follows:

- i: wave energy transport by the group velocity; relative wave power;
- ii: wave energy transport by the projected tidal current;
- iii: transport of the kinetic energy of tidal current;
- iv: work done by the current against the wave radiation stress (i.e., energy exchange between waves and currents; the radiation stress represents the mean wave-induced excess momentum flux).

The total energy flux due to waves E_f (i.e., the absolute wave power) is defined as the sum of the first and second terms in Eq. (4). Additionally, due to the Doppler shift induced by the current [14], the angular frequency of waves from the perspective of a stationary observer (i.e., the absolute frequency σ_0) will be different from the intrinsic/relative wave frequency σ (i.e., the wave frequency observed when moving with the current, for which linear wave theory applies). We have,

$$\sigma_o = \sigma + ku \tag{5}$$

which as expected predicts a reduced/increased relative frequency for a co-flowing/opposing current, respectively.

The presence of additional terms in Eq. (4) introduces some difficulties in the direct application of the energy flux conservation law. For this reason, in state-of-the-art phase-averaged wave models (e.g., SWAN [17]) one instead expresses the conservation of wave action E/σ [18,19] which, unlike the total wave energy flux, is conserved in the presence of an ambient current. In a one-dimensional case, it reads,

$$\frac{\partial (E/\sigma)}{\partial t} + \frac{\partial \{ [u(x,t) + C_g](E/\sigma) \}}{\partial t} = 0 \tag{6}$$

Besides wave energy – or wave height – the wave angular frequency and wavenumber are unknown in the above equation, which requires using additional equations. Assuming linear wave theory, these are the linear dispersion relationship Eq. (2) and the conservation of wave crests equation (i.e. $(\partial k/\partial t) + (\partial \sigma_o/\partial x) = 0$; [20,14]), which together with Eq. (5) lead to the well-posed system of equations,

$$\begin{gathered} \frac{\partial k}{\partial t} + \frac{\partial \{ \sigma + ku(x,t) \}}{\partial x} = 0 \\ \sigma^2 - gk \tanh(kh) = 0 \\ \frac{\partial \left(H^2/\sigma \right)}{\partial t} + \frac{\partial \{ [u(x,t) + C_g(k,h,\sigma)] H^2/\sigma \}}{\partial x} = 0 \end{gathered} \tag{7}$$

By replacing σ from the second into the first Eq. (7), each of the above equations can be independently solved for k, σ, and H, respectively.

Note that, using Eq. (5), the dispersion relationship for the

[1] $\frac{1}{T}\int_0^T \int_{-h}^{\eta} p_D u_w \, dz dt$, where p_D is the dynamic pressure and u_w is the horizontal wave induced particle velocity, and η the wave surface elevation.

[2] $E_{tf} = \frac{1}{T}\int_0^T \int_{-h}^{\eta} \left[p_D + \rho g \eta + \frac{1}{2} u \rho \left| \mathbf{u} + \mathbf{u_w} \right|^2 \right] u_w dz dt.$