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# The role of tidal asymmetry in characterizing the tidal energy resource of Orkney

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When selecting sites for marine renewable energy projects, there are a wide range of economical and practical constraints to be considered, from the magnitude of the resource through to proximity of grid connections. One factor that is not routinely considered in tidal energy site selection, yet which has an important role in quantifying the resource, is tidal asymmetry, i.e. variations between the flood and ebb phases of the tidal cycle. Here, we present theory and develop a high-resolution three-dimensional ROMS tidal model of Orkney to examine net power output for a range of sites along an energetic channel with varying degrees of tidal asymmetry. Since power output is related to velocity cubed, even small asymmetries in velocity lead to substantial asymmetries in power output. We also use the 3D model to assess how tidal asymmetry changes with height above the bed, i.e. representing different device hub heights, how asymmetry affects turbulence properties, and how asymmetry is influenced by wind-driven currents. Finally, although there is minimal potential for tidal phasing over our study site, we demonstrate that regions of opposing flood- versus ebb-dominant asymmetry occurring over short spatial scales can be aggregated to provide balanced power generation over the tidal cycle.

## 1. Introduction

Site selection for tidal energy projects is not simply a case of identifying sites with an appropriately large peak tidal current [1]. Rather, it is important to consider how the resource varies over a variety of time scales, from seasonal, to lunar, to semi-diurnal, and down to turbulent time scales [2]. It is also important to consider whether tidal energy extraction will significantly impact on the resource [3,4], and associated coastal processes such as sediment transport and morphodynamics [5].

Site selection for tidal energy converter (TEC) arrays consists of various practical and economical constraints, such as the magnitude of the resource, water depths appropriate for the chosen technology, navigational constraints, proximity to a suitable port for installation and maintenance, and grid connections [6,7]. However, one factor which is not routinely considered in site selection is the importance of tidal asymmetry [8]. From a resource and device perspective, it is clearly beneficial to select sites where the tidal currents have an equal magnitude between the flood and ebb phases of the tide (tidal symmetry), and less desirable to exploit sites which have either strong flood- or ebb-dominance (tidal asymmetry). Tidal asymmetry not only affects the primary variables of the flow field such as velocity and water elevation – it is also expected to cause asymmetry in turbulence properties such as Reynolds stresses and turbulent kinetic energy, important variables in site selection [9]. For instance, there is strong turbulence asymmetry in the eastern English Channel due to the presence of quarter diurnal tidal harmonics [10]. It has also been demonstrated that exploitation of asymmetrical sites could have a greater environmental impact on morphodynamics than symmetrical sites, because of the way in which tidal energy extraction alters residual sediment transport pathways [11].

Tidal waves are progressively distorted and dampened as they propagate in shallow-water coastal regions [12]. Although tidal waves in such regions still satisfy the criteria of long waves (i.e. wavelength is much greater than water depth), in shallow water the amplitudes of the waves become a significant fraction of the total water depth [13]. As a result of these non-linear shallow-water processes, tidal waves in such regions are often more complex than their linear wave counterparts, with the occurrence of double high or low water, and asymmetries observed in velocity time series due

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to the presence of overtides.[1] Tidal asymmetry can also be generated by other mechanisms such as topographic features (e.g. in the wake of an island) [14], or by meteorological effects. In the latter case, persistent seasonal baroclinic flows of up to 0.2 m s$^{-1}$ in stratified shelf sea regions can play an important role in generating asymmetry [15], and hence affect the net tidal energy resource, and affect mechanisms such as the dispersal of pollutants and marine organisms [16].

In this paper, we discuss the origin of tidal asymmetry and its theoretical impact on net power output (Section 2). Next, we describe our Orkney case study (Section 3), to which we apply the 3D ROMS ocean model (Section 4). In Section 5, we present model results along a 30 km length of an energetic tidal channel in Orkney, demonstrating how the model simulations agree with theoretical estimates of tidal asymmetry. Finally, we discuss the implications of the simulated tidal asymmetry on the tidal energy resource, including a consideration of vertical variability and the potential for tidal phasing over small spatial scales (Section 6).

## 2. Tidal asymmetry

Since astronomical tides are generated by the combined gravitational forces of the Sun and the Moon, the frequencies of tidal constituents in the deep oceans directly relate to lunar or solar days, and can be expressed in terms of diurnal and semi-diurnal components. The propagation of (barotropic) tides in the deep ocean is primarily governed by linear processes, where their interactions generate sub-harmonic tides [12]. For instance, the combination of the principal semi-diurnal lunar ($M_2$) and solar ($S_2$) tidal constituents describes the spring neap cycle, with a frequency of,

$$\omega_{S_2} - \omega_{M_2} = \frac{1}{12\text{ h}} - \frac{1}{12.4206\text{ h}} = \frac{1}{14.765\text{ days}} \quad (1)$$

where $\omega$ is the angular frequency.

Over continental shelves and in shallow coastal waters, other non-linear forces and processes such as friction, advection (due to advective inertia forces) and diffusion (due to turbulence) become increasingly responsible for the dynamics of the tides. As a result, the tidal signal is more complex in such regions, and can no longer be represented by simple linear superposition of semi-diurnal and diurnal components. Using the concept of Fourier series, by combining higher frequency tidal components or super-harmonic tides, any non-linear tidal signal can be reconstructed. Unlike astronomical tides, super-harmonic tidal components are generated by localised shallow water forces. Accordingly, the non-linear interaction of an astronomical tidal component with itself and other tidal components generates overtides and compound tides, respectively, with higher frequencies, e.g.

$$\begin{aligned}&M_4(2\omega_{M_2}), M_6(3\omega_{M_2}), S_6(3\omega_{S_2}), MS_4(\omega_{M_2}+\omega_{S_2}),\\ &MN_4(\omega_{M_2}+\omega_{N_2}), \cdots\end{aligned} \quad (2)$$

Overtides and compound tides are the main causes of tidal asymmetry, and their role in understanding and accurately simulating tides is very important in some regions [17]. Using simple mathematics, it can be easily shown that the nature of tidal asymmetry is related to the phase difference between semi-diurnal and quarter-diurnal tidal constituents. Further, Speer et al. [18] showed that,

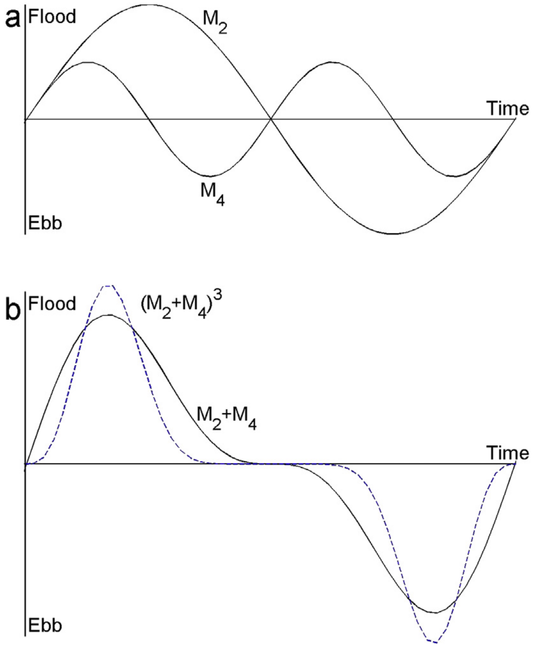

**Fig. 1.** Combination of $M_2$ and $M_4$ tidal currents resulting in tidal symmetry. (a) Tidal currents for individual constituents, and (b) tidal currents (solid line) and power (blue dashed line) resulting from superposition of $M_2$ and $M_4$ constituents. Based on [19]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

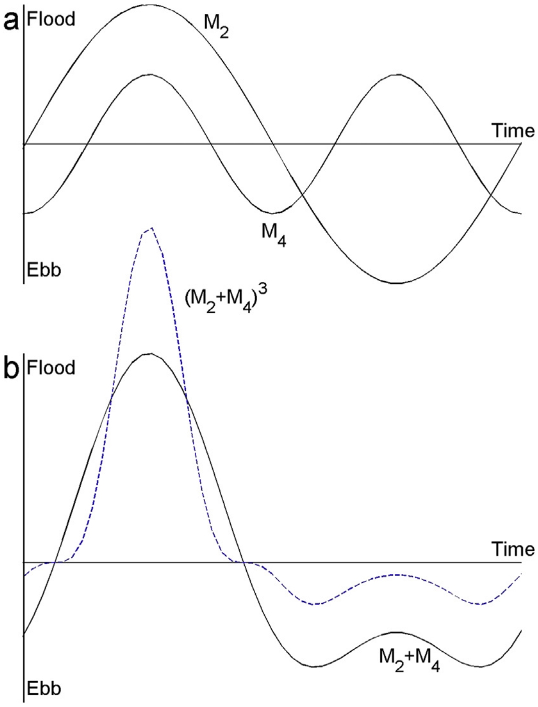

**Fig. 2.** Combination of $M_2$ and $M_4$ tidal currents resulting in tidal asymmetry. (a) Tidal currents for individual constituents, and (b) tidal currents (solid line) and power (blue dashed line) resulting from superposition of $M_2$ and $M_4$ constituents. Based on [19]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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[1] A harmonic tidal constituent with a speed that is an exact multiple of one of the fundamental constituents.