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Reynolds stress and turbulence estimates in bottom boundary layer of Fall of Warness ☆

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ABSTRACT

A broadband acoustic Doppler current profiler (ADCP) moored on the seabed at 42 m depth has been used to observe the mean and turbulent flow components in the tidally energetic Fall of Warness channel over two tidal cycles. The Reynolds stress has been estimated from the difference in variance between the along-beam velocities of opposing acoustic beams. Near bed stress at 2.63 m above seabed (mab) exceeds 7.5 Pa at the time of mean flow (speed of ~1.3 m s^{-1}) while the ebb stresses are limited to ~3.31 Pa during the peak ebb, mean, flow of ~1.3 m s^{-1}. The production of turbulent kinetic energy (TKE), P was found to be negative below 2×10^{-9} W m^{-3} and up to 6×10^{-4} W m^{-3} was estimated during flood flows and decreasing to 3×10^{-4} W m^{-3}. The TKE dissipation rate ε was estimated by inertial dissipation method (IDM) with the greatest value of 2.43×10^{-2} W m^{-3} observed near the seabed around maximum ebb, falling to 5.75×10^{-5} W m^{-3} around slack water. The comparison between P and ε was performed by calculating individual ratios of P corresponding to ε using a bootstrap resampling technique. The study shows that the ratio ε/P averaged over whole flood and ebb were found to be ~0.4138 and ~0.4177, respectively, indicating that production exceeded dissipation. The uncertainties in Reynolds stress estimates due to instrument noise were found to be 3×10^{-4} Pa while 4.52×10^{-2} Pa can be attributed to the uncertainties due to the increase in the flow-related component.

1. Introduction

The global drive for renewable energy research and development arose from the need to; reduce green house effect, combat the inevitable decline, in traditional energy provision by fossil fuels and to reduce the level of environmental pollution due to energy production and consumption. Tidal current energy conversion systems have been noted as one of the viable technologies owing to other inherent predictability, reliability and minimal environmental impact. In addition, the natural resource is cheap and continuous. Unlike wind and solar energy, it is not considered weather dependent.

The World Offshore Renewable Energy Report 2002–2007, released by the Department of Trade and Industry, suggests that an estimated 3000 GW of tidal energy is available. Scottish Enterprise has estimated that, about 34% of UK electricity demand can be produced from tidal currents; this represents a huge untapped resource. Alternative energy sources hold the key towards the future, without them, energy crises are inevitable.

A typical site for a tidal current energy device is a challenging environment; exhibiting large scales of turbulent motion. A better understanding of the nature of turbulence in tidal channels is therefore, a key goal in the successful installation and operation of tidal energy devices. Understanding the structure of turbulence, will make it possible to be able to predict its appearance and possibly manage or control its influence. Large scale motion has been observed from previous work carried out on real flows and these may take the form of volumes of random motion or more organised vortices and shear flows. Rapid velocity changes within large scale turbulence imply that significant fluctuations in loading may be applied to a submerged tidal current energy device by such flow behaviour.

The design of modern marine current turbines is currently being driven by the extreme loads imposed upon the turbine. These loads come in two forms, both of equal importance to the design of a reliable turbine. The first comprises the extreme loads associated with the strongest tide and the second is the cyclic loads that continually pose a treat of fatigue damage to the turbine by turbulence in the inflow. As noted by Madsen et al. [1], the extreme loads during normal operation in turbulent conditions may exceed the design loads in wind turbine. The fatigue damage to critical components, such as the blades, is dominated disproportionately by the highest operating loads even though their rate-of-occurrence is relatively small. (Most of the flows occurring in nature are turbulent (McDonough [3])). Turbulence

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Nomenclature

u_*	shear velocity, m s^{-1}
u	along-stream velocity, m s^{-1}
z	height above bed, m
v	across-stream velocity, m s^{-1}
P	TKE production, W m^{-3}
w	vertical velocity, m s^{-1}
A_z	Eddy viscosity, m^2 s^{-1}
S	TKE density, J m^{-3}
b_i	along-beam velocities, m s^{-1}
Re	Reynolds number, $\Omega r^2/v$
$\ddot{u}$, $\ddot{v}$, $\ddot{w}$	velocities instrument coordinate system, m s^{-1}
k	wavenumber
f	frequency
$\bar{u}$	mean velocity, m s^{-1}
M	ensemble number
$\bar{u}$	mean velocity, m s^{-1}
$\overline{x'^2_i}$	along-beam velocity variance due to turbulent fluctuations

Greek symbols

τ	shear stress, Pa
μ	dynamic viscosity, N s m^{-2}
τ_b	bed shear stress, Pa
ρ	fluid density, kg m^{-3}
τ_x	along-stream vertical turbulent stress, Pa
τ_y	across-stream vertical turbulent stress, Pa
ε	TKE dissipation, W m^{-3}
θ	beam angle, °
ϕ_1	pitch angle, °
ϕ_2	roll angle, °
γ	constant
α	Kolmogorov constant
σ_b^2	along-beam velocity variance due to instrument noise
σ_{st}	Reynolds stress uncertainties, Pa
σ_{sh}	Shear estimate uncertainties, 1 s^{-1}
σ_{pr}	TKE production uncertainties, W m^{-3}

Subscripts

n	integer
i	integer

is a manifestation of the flow and originates in the instability of shear flows. It can be characterised by a rotational three-dimensional motion, which generates large gradients of velocity at small scales and therefore promotes dissipation of kinetic energy into heat. This makes turbulence a highly dissipative process and therefore a source of energy that must be present to maintain the process. In 1883 Osborne Reynolds published the first paper, which described the transition from laminar to turbulent flow. He concluded that the transition occurs at higher speeds, when Reynolds number (Re), which determines resistance to the flow, exceeds 1.3×10^{10} ($Re=UD/v$ where U is an average velocity in the water column, D is a stream distance, v is a kinematic viscosity) (Reynolds [2]).

In coastal boundary layers the transition from laminar to turbulent flow is affected several parameters: such as pressure distribution in the external flow, roughness of the seabed and the nature of disturbances. The presence of bed roughness favours the transition by decreasing the critical value of the Reynolds number. The existence of irregularities on the seabed gives rise to additional disturbances in the flow and, as a consequence, a lower degree of amplification is sufficient to effect a transition from laminar to turbulent flow. Another important parameter affecting the stability of the flow is density variation. When the flow has density stratification, turbulent mixing can be strongly affected. This is true especially in the vertical direction where the parcels of fluid must be moved against hydrostatic forces.

At high water velocities and because of edge effects and surface roughness of structures, given that water is a viscous fluid, flows in a marine current turbine system are turbulent, rather than laminar. The tendency of water molecules to resist shear forces, due to the presence of viscosity, causes them to move irregularly. The shear stresses within a flow field tear the fluid into highly energetic, irregular, and three-dimensional eddies, with scales ranging from the size of the flow passage down to unity (Miller [4]). These eddies exist randomly in space and time in turbulent shear flows (Nezu and Nakagawa [5]). Within a turbine system, it would be difficult to separate the effects of normal forces (that cause pressure) from tangential forces (that cause shear stress), but rather the fluid stress will be a combination of the two.

At the bottom of the ocean the water flowing above the seabed causes stress which extends into the water column. Near the bed, the velocity decreases due to the friction. The part of the flow where the velocity is affected by the bed is called the boundary layer. In the laminar boundary layer the velocity shear ($\partial u/\partial z$) increases linearly with increase in shear stress (τ):

$$\tau = \mu\frac{\partial u}{\partial z}, \tag{1}$$

where μ is the dynamic viscosity. At a sufficiently high Reynolds number the flow in the boundary layer becomes turbulent due to instability present in the flow. As a consequence the flow develops a highly random character with rapid irregular fluctuations of velocity in space and in time. The velocity at any point in space (u) can be described by its time average ($\bar{u}$) and fluctuating part (u'): $u=\bar{u}+u'$. It can be seen that the fluctuating parts of velocity vector give rise to additional stresses in the flow, called Reynolds stresses which increase with distance from the boundary and with the intensity of turbulence.

Therefore, a total shear stress in the turbulent bottom boundary layer is a product of viscous and Reynolds stress. It varies with height above the bed, but near the bed, reaches the constant value defined as the bed shear stress (τ_b). This parameter makes it possible to define a shear velocity (u_*) that represents the strength of turbulent velocity fluctuations near the bed: $u_* = \sqrt{\tau_b/\rho}$: $u_*\approx\sqrt{\overline{u'w'}}$. From experimental studies, for relatively smooth bottoms the friction velocity was found to be around 0.2 cm s^{-1} for flat bottoms (Chriss and Cadwell [6]), 1 cm s^{-1} when a surface swell occurred (Grant et al. [7]), and few cm s^{-1} when bottom roughness was present (Cacchione et al. [8]).

The measurement of turbulent parameters in tidal flows presents oceanographers with a difficult problem, since it is necessary to obtain rapid measurements of velocity at small spatial scales in an environment in which large stresses operate and where, away from the bottom boundary, there is no fixed reference for velocity measurement. Turbulent stresses, or Reynolds stresses, represent the transport of momentum by turbulence and thus can control the vertical structure of turbulent environmental flows. Knowledge of Reynolds stresses along with mean velocity profiles allows the eddy viscosity, the most common parameterization of vertical mixing due to turbulence, to be computed. In the shallow coastal ocean, measurement of Reynolds stresses is complicated by the presence of surface waves. Although for small-amplitude irrotational waves the horizontal and vertical components of wave orbital velocities are 90° out of phase and therefore should have zero covariance, very small tilts in sensor alignment, or real wave stress associated with a sloping bed, for example, lead to a covariance between horizontal and vertical velocities that can contaminate or even dominate Reynolds stress measurements. Additionally, waves often occupy the same frequency range as turbulence in the shallow coastal ocean, and therefore wave