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Wavelet-based vortical structure detection and length scale estimate for laboratory spilling waves

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ABSTRACT

Turbulent flow fields under spilling breaking waves are measured by particle image velocimetry and analyzed using the wavelet techniques in a laboratory surf zone. The turbulent vortical structures and corresponding length scales in the flow are detected through the eduction of the most excited mode with local intermittency measure that is found to correlate with the passage of the structure. Distributions and evolution of the educed vortical structures are presented and discussed. Packets of vortical structures with high intermittency is observed to stretch downward below the initially low-intermittency trough level, indicating these structures play a crucial role in turbulent mixing below the trough level. It is found that the probability density functions of the intermittent energy of the educed structures, vorticity and swirl strength display an exponential decay. Ensemble-averaged length scales of the educed vortical structures are found to be about 0.1 to 0.2 times the local water depth, close to the turbulent mixing length reported in the surf zone. The Kolmogorov microscale is evaluated and the turbulent mixing length is estimated using the $k-\varepsilon$ relation and mixing length hypothesis. The $k-\varepsilon$ relation may overestimate the mixing length scale for energetic descending eddies.

1. Introduction

Wave breaking plays an important role in transferring wave energy, momentum, heat, and mass at the air–sea interface. In the process, wave motion is converted from an irrotational flow into a rotational turbulent shear flow, and wave energy is dissipated. Turbulence generated by wave breaking also brings sediment into suspension from the bed and transported by the wave-induced current. Accordingly, turbulence under breaking waves has been an important issue for many researchers such as geophysical scientists, environmental and coastal engineers.

Recent advances in wave breaking study have led to better understanding of its mechanism. Descriptive representations of surf zone wave breaking, such as the crest rolling, water splashing and vortex generation, were carried out using flow visualization techniques (e.g., Nadaoka et al., 1989; Lin and Hwung, 1992). More advanced quantitative insights for surf zone dynamics were achieved using point measuring techniques such as laser Doppler velocimetry (LDV) (e.g., Stive, 1980; Nadaoka et al., 1989; Ting and Kirby, 1996; Cox and Kobayashi, 2000; Stansby and Feng, 2005; Longo, 2009). However, instantaneous spatial distribution and derivation of certain physical quantities cannot be obtained with LDV, and spatial derivatives were estimated through the Taylor hypothesis (i.e., $\partial/\partial t = -C(\partial/\partial x)$ with C being the wave phase speed). This assumption may be questionable in the analysis of turbulence transport in surf zone because turbulent fluctuations are not small if compared to the mean flow (Ting and Kirby, 1995; Kimmoun and Branger, 2007). Recently, more and more flow field and turbulence measurements in surf zones were performed using particle image velocimetry (PIV) due to its full-field advantage of obtaining the entire velocity map (Govender et al., 2002; Kimmoun and Branger, 2007; Ting, 2008; Huang et al., 2009a,b).

For flows inside a surf zone, it is known that turbulence is primarily generated in the crest region through the rolling and water splashing process (Peregrine, 1983; Christensen et al., 2002; Watanabe et al., 2005; Kimmoun and Branger, 2007; Huang et al., 2009a). Turbulence in that region is observed to stretch into the interior water column below the trough level by convection and turbulent diffusion after the passing of the developed turbulent bore (Kimmoun and Branger, 2007; Huang et al., 2009a). The downward stretching of turbulence is found to associate with a large-scale eddy motion — the so-called obliquely descending eddy denominated by Nadaoka et al. (1989). The eddy is responsible for excessive mass flux, and it enhances momentum transport in breaking waves. However, such a large turbulent motion occurs intermittently and its instantaneous burst of turbulent kinetic energy and Reynolds stress could not be explained

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using phase-averaged quantities (Chang and Liu, 1998; Foster et al., 2006; Huang et al., 2010). The large turbulent motion contributes to significant turbulence intensity, and possibly brings sediment into suspension (Cox and Kobayashi, 2000). Indeed, Beach and Sternberg (1988) reported that intense and intermittent events of sediment suspension occur above the boundary layer inside the surf zone. Voulgaris and Collins (2000) also found that vortices induced by breaking waves and bores are the main mechanism responsible for sediment resuspension. This motivates us to investigate vortical structures under surf zone breaking waves. Not only are practical issues relating to sediment transport relevant to the study, the study also intends to understand the physical process of surf zone dynamics pertaining to the relationship between the vortical structures and turbulence.

Reynolds decomposition using the ensemble-average method is a useful means to quantify turbulence characteristics in surf zone. Magnitudes of turbulent intensity and Reynolds stresses can be quantified after decomposing turbulent fluctuations and average quantities (e.g., Stive, 1980; Ting and Kirby, 1996; Govender et al., 2002; Stansby and Feng, 2005; Kimmoun and Branger, 2007; Huang et al., 2009a). In addition, turbulence transport can be realized through estimates of physical terms in the k equation (k is the turbulent kinetic energy) (e.g., Ting and Kirby, 1996; Govender et al., 2004; De Serio and Mossa, 2006; Kimmoun and Branger, 2007; Huang et al., 2009a,b). The $k-\varepsilon$(ε is the turbulent dissipation) (e.g., Lin and Liu, 1998) and $k-l$ (l is the turbulent length scale) (e.g., Zhao et al., 2004) turbulence closures were successfully included in the Reynolds-averaged Navier–Stokes models to simulate surf zone wave breaking. However, these models adopt the one-point statistical closure method and the influence of large-scale motion from turbulent eddies was ignored (Bonnet and Delville, 2001).

In recent years, turbulent flows are described as the mixing of coherent structures that are composed of different length scales of motion. Coherent structures that are recognized as organized vortical motions significantly contribute to fluid entrainment, mass transport, and momentum and heat mixing and advection. They play an important role in large-scale dynamics of turbulent flows, and affect the motion of small scale turbulence (Robinson, 1991; Bonnet and Delville, 2001; Camussi, 2002). Although there is not a universal and definitive definition of coherent structure in turbulent flows (Ruppert-Felsot et al., 2009), a coherent structure is generally recognized as an "organized" vortical structure that exhibits significant phase-correlation with itself over a range of space and time (Hussain, 1986; Robinson, 1991). Coherent structures can be identified using several methods such as the proper orthogonal method and wavelet analysis (see a summary in Bonnet et al., 1998; Adrian et al., 2000; Bonnet and Delville, 2001).

In the present study, wavelet analysis is adopted to decompose velocity signals into different length scales. Wavelet techniques have been applied to observe coherent vortical structures in different turbulent flows measured by PIV (e.g., Camussi, 2002; Schram et al., 2002; Camussi and Felice, 2006; Ruppert-Felsot et al., 2009). In addition, Longo (2009) used the wavelet technique to analyze velocity signals measured by LDV using Taylor hypothesis in the pre-breaking region. In the study, no data are available in the surf zone because LDV is ineffective in the aerated region due to signal drop-out caused by the entrained bubbles. Vortices with length scales ranging from ten times of the Kolmogorov microscale to one wavelength that carries most turbulence energy under the wave crest were found. However, more studies are needed to clarify the length scales in the surf zone. For example, the largest eddies in the turbulent flows are known to be determined by the boundary conditions of the flow and their size should be of the same order of magnitude of the flow domain (Rodi, 1980). In surf zone breaking waves, turbulent mixing length scales are found to be in the order of 0.1–0.3 times the local water depth (Svendsen, 1987; Ting and Kirby, 1996; Govender et al., 2004). This suggests the vortical scale should be of the order of local water depth instead of the wavelength. More evidences are needed to clarify the properties of vortical structures in the surf zones.

The objectives of this study are to educe vortical structures based on the wavelet technique and intermittency measure, and to estimate the length scales and statistical properties of the educed vortical structures under spilling breaking waves in a laboratory surf zone. Vortical structures inside a surf zone have received little attention due to a lack of suitable measurement tools. It is difficult to reveal the spatial properties of vortical structures using single-point measurement instruments. Full-field velocity maps obtained using PIV allow researchers to examine such spatially-dependent turbulent structures. Even so, to the best of the authors' knowledge, few studies have been conducted to investigate the spatial properties of vortical structures inside a surf zone. The structure of the present study is organized as follows: experimental setup and facilities are described in Section 2. The wavelet technique and local intermittency measure for educing vortical structures and identifying length scales are

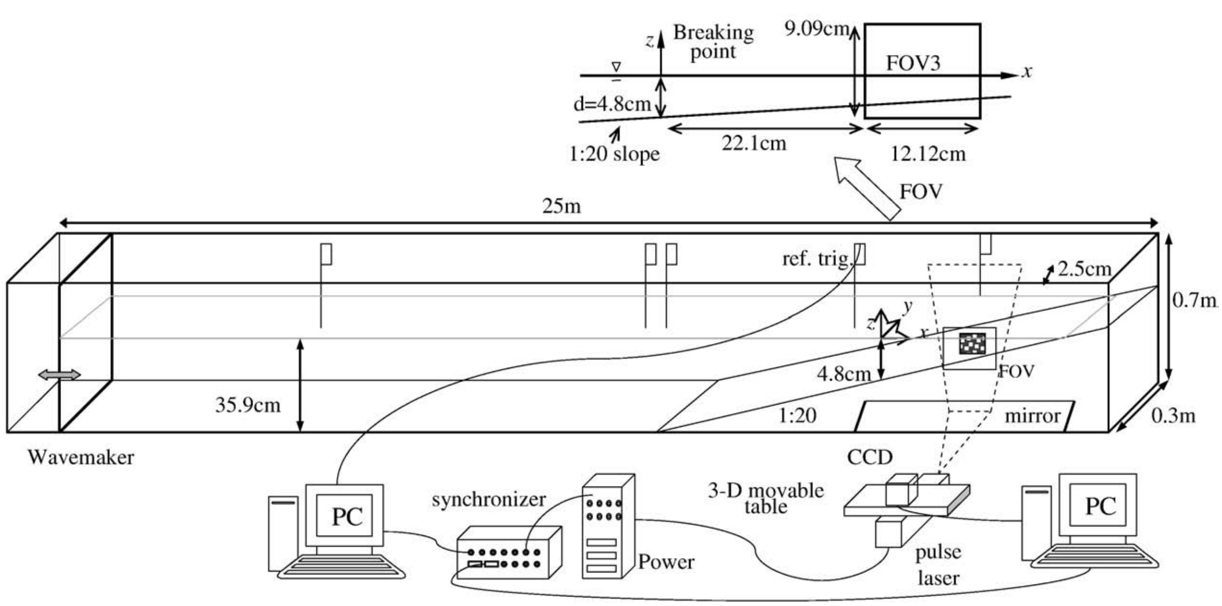

Fig. 1. Experimental facilities and setup.