Applied Ocean Research 63 (2017) 170–183

Contents lists available at ScienceDirect

Applied Ocean Research

journal homepage: www.elsevier.com/locate/apor

Distribution of eddy scales for wave current combined flow

Sayahnya Roy, Koustuv Debnath*, Bijoy S. Mazumder

Fluid Mechanics and Hydraulic Laboratory (FMHL), Department of Aerospace Engineering and Applied Mechanics, Indian Institute of Engineering Science and Technology (IIEST), Shibpur 711103, India

ARTICLE INFO

Article history:
Received 20 August 2016
Received in revised form
26 December 2016
Accepted 4 January 2017

Keywords:
Eddy
Probability density function
Reynolds stresses
Waves
Wavelet analysis

ABSTRACT

This paper illustrates the modulation of the eddy scale distribution due to superimposition of surface wave on only current flow. Time series data of three-dimensional velocity components were measured in a laboratory flume by a three-dimensional (3D) 16-MHz micro-acoustic Doppler velocimeter (Micro-ADV). The velocity time series of only current case and waves following the current were analysed to obtain the phase-averaged mean velocities, turbulent intensities, and Reynolds stress. The probability density function of phase-averaged stream-wise and vertical velocity fluctuations showed bimodal oscillations towards the free surface for higher frequency surface waves. It was revealed that surface waves along the current effectively decrease the intermittency of turbulence of the only current flow. Surface wave changed the intermittent structure of only current flow by modulation of the energy cascade mechanism of the only current flow by introduction of wave induced length scales. Also the scale of the finer dissipative eddies were prominently enhanced by the increase in surface wave frequency. Wavelet analysis of time series of velocity signals provided information on the eddy scale and their frequency of occurrence. It was found that the large eddies are carried by the crest regions of the progressive wave while the small scale eddies are carried by the trough regions.

1. Introduction

In the nature, tidal waves generally hold the attribute of waves following a current and are regularly observed in the coastal zones. Thus, studying the mechanics of the wave current interaction is of great importance for understanding: the stability of bed sediments; different physiological processes of aquatic species, among many others. Further quantification of the scales and energy content of eddies is required for improved design of offshore structures and safe navigation. Many experiments have been reported towards understanding the flow characteristics due to wave-current interaction for the last four decades. Based on laboratory flume experiments on wave amplitude attenuation Hoften and Karaki [1] reported that the turbulence energy is generated near the free surface due to the interaction of the wave induced Reynolds stresses and the fluctuating velocity gradients. The study also reported that the energy dispersed towards the downward direction and dissipated at the bottom by the bed shear stress. Kemp and Simons [2] also carried out experiments in a laboratory flume on rough as well as a smooth bed for waves following a current. Ismail and Wiegel [3] reported that turbulent fluctuations were small for wave and current combined flow relative to turbulence generated due to only wave. Van der Kaaij and Nieuwjaar [4], Van Kampen and Nap [5] and Van Rijn et al. [6] studied the velocity distribution for sediment-laden flow containing the different size of fine sediment under the combination of irregular waves and current. From all laboratory tests, it was found that the mean velocity increased from the bed to a certain vertical distance and thereafter decreases towards the free surface. Umeyama [7] showed that the maximum magnitude of Reynolds stress decreased to two-third of that of the only current flow. Umeyama [8], Umeyama and Shinomiya [9], Umeyama and Matsuki [11], Umeyama and Nguyen [12] observed the water particle velocity of internal waves using the PIV system to obtain consecutive velocity fields. Thus it is evident from the previous studies that surface wave can modulate turbulence field of the only current flow. However, no study has been reported towards understanding the spatial as well as the temporal distribution of different eddy scales within the flow field for a wave current interacting flow. The present study aims to provide improved insight into the scales of eddies generated due to wave-current flow using wavelet transform. By the use of wavelet transform, velocity signal can be decomposed into the frequency and time domain. Wavelet transform has been applied to different fields of science and engineering for analyzing random signals (e.g., Niu and Sivakumar [13]; Sehgal et al. [14,15]; Shoaib et al. [16]; Wang et al. [17]). Morlet [18] first used wavelet transform to study seismic signals. Later, Farge [19] reviewed its application to velocity time series for quantification of turbulence.

---

* Corresponding author.
E-mail address: debnath_koustuv@yahoo.com (K. Debnath).

http://dx.doi.org/10.1016/j.apor.2017.01.005

Meneveau [20] reported that the orthonormal wavelet transform can be applied without difficulty similar to Fourier analysis and that the physical interpretation of the wavelet coefficients to different turbulence scales is more logical than that of the coefficients of globally extended functions such as Fourier modes. Recently, Wang et al. [17] stated that the auto-correlation of wavelet coefficients calculated from the experimental data can be used to examine the turbulent coherent structures.

In spite of all these studies, no investigation has been carried out to explore the mechanism of the turbulent eddy modulation by inducing wave energy at the water surface. Thus, the present study intends to explore the effect of superimposed surface waves on only current flow in the context of eddy scale modulation. Further, the effect of superimposed surface wave on the intermittent structure of turbulence is presented.

2. Experimental method

2.1. Test channel

Experiments were performed in a specially designed tilting flume (Fig. 1) of 18.3 m length, 0.9 m wide and 0.9 m deep maintained at a constant slope of 0.00025 housed at the Fluid Mechanics and Hydraulics Laboratory (FMHL), Department of Aerospace Engineering and Applied Mechanics, Indian Institute of Engineering Science and Technology (IIEST), Shibpur, India. The test section was situated 11 m from the flume entrance. Transparent Perspex sidewalls at the test section aid in vizualization of the flow. The flow at the inlet passed through a series of honeycombs made of stainless steel. Those honeycombs were used to break the large scale turbulent structures and to provide smooth entry to the flume. The discharge control valve was gradually opened to accomplish desired discharge and the valve opening was locked for a constant discharge during an experiment. In order to maintain the flow depth of $h = 20$ cm, tailgate located at the downstream end of the flume was adjusted. A vertical turbine pump was used to supply water from the sump to the flume inlet.

A custom designed vertically reciprocating horizontal triangular crosssection plunger type wave maker was positioned near the inlet of the flume to produce surface waves (Fig. 1). The wave-maker was fabricated in the Fluid Mechanics and Hydraulic Laboratory workshop. Two 20 cm diameter pulleys were fitted at the end of a 3.5 cm diameter shaft. A worm gear was fitted at the middle position of the shaft and was connected with a speed reduction gear train. In order to convert the rotational motion to reciprocating motion slider-crank mechanism was used. One end of the crank was linked at the 5 cm distance from the center of each pulley. The connecting bar of the crank was permitted to pass through a guide, in order to restrain the lateral displacement of the crank. A triangular plunger of slope $-15/11$ was fixed at both ends of those connecting bars (Fig. 1). One 2 (hp) DC motor was used to provide the rotational motion of the gear train. Power supplied to the motor via a DC Variac, controlled the rpm of the motor for generating the desired wave frequency. Wave absorber was placed close to the downstream tail gate for arresting reflection of waves from the tailgate. Vertical to and fro motion of the horizontal triangular plunger produced propagating surface waves on the unidirectional current.

2.2. Measurement methods

A 16 MHz Micro-Acoustic Doppler Velocimeter (ADV) was used to measure all three components of instantaneous velocity time series at a sampling frequency of 40 Hz. The ADV has been used in a variety of applications for quantification of turbulence, such as over dunes (Mazumder et al. [21], Mazumder and Ojha [22]), circular cylinder (Debnath et al. [23]), hemisphere (Barman et al. [24]) cube (Singh et al. [25]) and many more. The ADV data were refined to eliminate spikes by a phase space threshold despiking method described in [26]. The data were “cleaned” by removing all communication errors, low signal-to-noise ratio data (<15 dB) and low correlation samples (<70%). This stage was performed by Win-ADV software which resulted in the removal of 1.8% of all collected velocity time series.

Table 1
Hydrodynamic Parameters for only current flow over a flat rigid surface.

Reynolds number [$R_e = Uh/\nu$]	5.96×10^4
Depth average stream-wise velocity [U (cm/sec)]	29.8
Mean flow depth [h (cm)]	20.0
Froude number [F_r]	0.212
Friction velocity (computed from the log law) [u_* (cm/sec)]	1.4

Table 2
Parameters for only current flow & wave following current.

	OCF	WFC1	WFC2
Time period [T (sec)]	0	1	0.5
Frequency [f (Hz)]	0	1	2
Mean flow depth [h(cm)]	20	20	20
Observed surface wave height [h_w (cm)]	0	2.0	3.15
Observed surface wave length [λ (cm)]	0	64.6	34.8
Depth average stream-wise velocity [U (cm/sec)]	29.8	28.3	28.1
Wave Reynolds number [$R_w = a^2\omega/\upsilon$]	0	2513	12469
Amplitude of the orbital motion near the bed [$\hat{a}$(cm)]	–	0.3	0.099
Orbital velocity [U_o(cm/sec)]	–	1.88	1.24
Wave boundary layer thickness [δ (cm)]	–	0.043	0.0199
Wavelength-mean depth ratio	–	3.25	1.75
Wave slope	–	3.52	9.72
Crank stroke [cm]	–	10	12.5

Note: OCF stands for current only; WFC1 and WFC2 stands for superimposed surface wave of frequency 1 Hz and 2 Hz respectively on only current flow.

The depth averaged velocity (U); the Froude number ($F_r = U/\sqrt{gh}$); the Reynolds number $\left(R_e = Uh/\upsilon\right)$ and the wave Reynolds number ($R_w = a^2\omega/\upsilon$) are given in Tables 1 and 2. Here $a = h_w/2$ is the surface wave amplitude, h is the flow depth; h_w is the wave height, ω is the angular frequency of the wave, υ is the kinematic viscosity of water, and g is the gravitational acceleration. In the present study for two different surface waves with frequencies $f = 1$ and 2 Hz, with $\lambda/h \approx 3.23$ and 1.74 and $\lambda/h_w \approx 32.2$ and 11.04 respectively have been studied. Goda [27] reported that in the nature surface waves with $\lambda/h_w \approx 1$to 11.04; and $\lambda/h_w \approx 4$ to 56 exist. Thus the present experimental surface waves represent the wave that are found in the nature. The present experimental surface wave conditions are categorized as follows: the frequency 1 Hz, $kh = 1.94 < \pi$ indicates the intermediate deep-water wave, and $f = 2$ Hz, $kh = 3.611 > \pi$ indicates the deep-water wave, where k is the wave number and equals $2\pi/\lambda$ (based on Dean and Dalrymple [28]). The surface wavelength λ and h_w were computed using digital image processing of images of waves at the test section of the channel similar to Barman et al. [24]. The amplitude ($\hat{a}$) of the orbital motion near the water bottom was calculated by using the formula obtained from the linear wave theory as (see Dean and Dalrymple [28])

$$\hat{a} = \frac{h_w}{2\sinh(2\pi h/\lambda)} \tag{1}$$

Table 2 shows that $\hat{a}$ for WFC1 ($f = 1$ Hz) is greater than WFC2 ($f = 2$ Hz). Further the orbital velocity $U_0(=\hat{a}\omega)$ where $\omega(=2\pi f)$is the angular wave frequency, $f(=1/T)$ is the frequency of the surface wave and T is the time period of oscillations (Table 2). Literature suggests that the wave boundary layer thickness can be obtained from the ratio between maximum amplitude and bottom roughness [29]. The wave boundary layer thickness δ for the present