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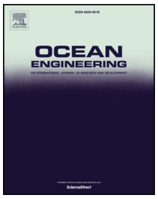

Distribution of turbulent energy in combined wave current flow

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ABSTRACT

The present study describes the turbulent flow characteristics of the steady flow and the combined wave-current flow for two different wave periods on unidirectional current. The turbulent kinetic energy distributions for steady flow and combined wave-current flow were analyzed to examine the turbulent energy production, pressure energy diffusion, turbulent energy dissipation and turbulent energy diffusion comprehensively. The result shows that the pressure energy diffusion drastically changes to a negative value due to the imposed surface wave on steady unidirectional current. This phenomenon indicates a low-pressure flow mode near the bed that probably affects the local sediment mobility in the coastal zone. Furthermore, the Taylor's frozen flow hypothesis was used to evaluate the dissipation rate of turbulent fluctuations to study the intermittent structure of turbulence due to imposed surface wave on steady current. Superposition of surface waves on unidirectional current significantly enhanced the finer dissipative eddies of the steady flow by the intonation of the energy cascade mechanism through wave-induced length scale.

1. Introduction

In the coastal region, wave and current simultaneously co-exists and form intricate flow structure in which different substantial processes with diverse temporal and spatial scales act together. The sediment entrainment, suspension and sea bed stability characteristics are examples of possible application that can benefit from an enhanced knowledge of the combined action between waves and steady current. Further, the combined effects of waves and currents in free surface flows have been the subject of many studies due to their impacts on coastal hydrodynamics. In this environment, horizontal and vertical velocities, as well as shear stresses, depend strongly on the interactions of waves and currents. The vertical profiles of these variables are modified and these are major issues in near shore waves and currents modelling. Hence, a large number of studies have been devoted to the study of combined effects of waves and steady currents in free surface flows.

1.1. Literature review

In order to study the combined effects of wave and current, majority of the previous experimental (for e.g., Kemp and Simons, 1982, Umeyama, 2005, 2009, Singh and Debnath, 2016, 2017 and others) and numerical modelling (Olabarrieta et al., 2010, Teles et al., 2013, Zhang et al., 2014 and others) were carried out over a flat surface to understand the wave-current interaction flow and turbulence characteristics. Generally the emphasis was given to examine the mean velocity profile and how it changed from that of the universal logarithmic law observed for steady flow along with the wave-current co-existing environment over a flat bed. It was also reported that the changes in the different turbulence parameters such as turbulence intensity and Reynolds shear stress due to the superimposition of a surface wave on the steady flow over a flat-surface. Furthermore, the mechanics of combined wave-current flow have been investigated theoretically by many researchers. For e.g., time-invariant one-layer turbulent eddy viscosity model developed by Grant and Madsen (1979) to describe combined wave and current motion. Myrhaug (1982) further extended the eddy viscosity model proposed by Grant and Madsen (1979) to developed analytical solution for the velocity profile in combined wave-current flow. Nielsen and You (1996) used Eulerian approach and suggested an eddy viscosity model by using several ad hoc assumptions to obtained fair results. However, Huang and Mei (2003) pointed out that, the model proposed by Nielsen and You (1996) was not entirely satisfactory with the experimental data. Thereafter, Huang and Mei (2003) studied the combined effect of waves and current and computed the turbulent shear stresses by using turbulence model which give the eddy viscosity

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straight from the flow variable. However, the model proposed by Huang and Mei (2003) is not easy to apply as suggested by Tambroni et al. (2015a). A simple model proposed by Tambroni et al. (2015a) for the wave-current interacting flow which agreed well with the experimental measurements of Kemp and Simons (1982), Klopman (1994) and Umeyama (2005). This new model may have a greater capability in simulating the combined wave-cuurent flow. Tambroni et al. (2015b) performed a flume experiment and study the impact of macroalgal mats on the wave and current dynamics. They reported that, in the case of waves combined with currents over macroalgae, the most significant effect of an algal mat is to damp velocity oscillations induced by waves, while the friction velocity remains essentially unchanged and the roughness parameter tends to increase slightly. In addition, they also reported that the time-averaged stream-wise velocity profile is very near to that observed in the presence of a current-only profile when comparatively feeble waves are superposed with a strong unidirectional current. Recently, Singh and Debnath (2016) performed a flume experiment to study the effect of surface wave on unidirectional current which mainly focused on the first and second order turbulent statistics. Spectra analysis was also performed by the author to obtain the oscillation pattern within the flow field that may affect the turbulent properties due to combined wave-current flow.

Most of the previous studies focused on the mean velocity profile arising from wave-current flow differs from that of steady flow (well-known logarithmic law), and the superposition of waves on a current enhances the turbulent intensity. But no study has been reported so far to understand the effect of the superimposed surface wave on the intermittent structure of turbulence as well as the turbulent energy flux. Therefore, the aim of this study is to examine the turbulent energy budget in terms of turbulent energy production, pressure energy diffusion, turbulent energy dissipation and turbulent energy diffusion in combined wave and steady current flow. Furthermore, the dissipation rate of turbulent fluctuations due to imposed surface wave on steady current is evaluated using Taylor's frozen flow hypothesis to study the intermittent structure of the turbulence.

The flow structure generated by combined wave-current flow is of great importance in the coastal zone for determining mass and sediment transport rates because the sediment is picked up by the waves and transported by the mean stream-wise flow (Umeyama, 2005). Therefore, the quantitative results from this study will be useful in model calibrations and in understanding sediment pickup, grain-sorting and transportation in coastal environments. It is to be noted here that this paper mainly focuses on the turbulent energy budget and its distribution over a flat rigid surface with change in surface wave frequency and not specifically sediment transport hydrodynamics. Although the rigid bottom surface used in the present study is not the correct representation in the coastal zone, this study will provide some understanding on energy distribution of the combined wave-current flow over the rigid bed without any added difficulty in measurement in the combined wave-current flow. Moreover, the use of static rigid surface allows a high spatial resolution of analysis and sampling very close to the boundary which is not possible with mobile bed in the field.

2. Experimental setup and description

Experiments were performed in a laboratory flume at the Fluid Mechanics and Hydraulic Laboratory (FMHL) of the Indian Institute of Engineering Science and Technology (IIEST), Shibpur, India. A specially designed flat bed open-channel flume of dimensions 18.3 m long, 0.90 m wide and 0.90 m deep was used for the experiments (Fig. 1). The discharge valve was gradually opened to achieve the desired discharge in the flume and the tailgate was operated simultaneously to ensure the desired flow depth, $h = 0.20$ m. The depth was maintained at a constant level during the experiment using a graduated scale attached to the side wall of the flume simultaneously, uniformity was checked by vernier gauge readings of the water depth. At the downstream end of the flume, the water spills freely into a large sump, from where it is recirculated into the flume using a vertical turbine pump (located outside the main body of the flume). The water flow after discharge from the pump passed through a series of wire-meshes placed at the upstream end of the flume to ensure smooth and uniform flow through the experimental channel (Singh et al., 2016).

A custom designed vertically reciprocating plunger type wave-maker was placed at the upstream end of the flume to produce surface waves (Fig. 1). The wave-maker was fabricated in the institute workshop. Two 20 cm diameter wheels were attached at the end of the spindle which was fitted with a worm gear at the middle position of the shaft and was connected with a speed reduction gear train. In order to transfer the rotational motion into reciprocating motion, a 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 plunger 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. The variac was used controlled the rpm of the motor for generating the desired wave frequency. The oscillation was produced at a right angle to the steady unidirectional current producing surface wave on unidirectional current. Description of the wave-maker and its working principle are given in detail by Singh et al. (2018a).

In the present study, two separate tests were carried out: (1) current-only flow test over the horizontal surface, and (2) tests over the horizontal surface with addition of surface-waves of the period, $T = 0.5$ and 1s on the current-only flow. Different flow parameters for which the tests were conducted are as follows: mean flow depth (h) is 20 cm, the depth-averaged velocity ($\overline{u}$) is 15 cm/s, flow Froude number $F_r(=U/(gh)^{0.5})$ is 0.085, flow Reynolds number $R_e(=\overline{u}h/\nu)$ is 30,000, where ν is the kinematic viscosity of water, g is the acceleration due to gravity. Further, the wave-height H and wave-length L_w were measured using a digital camera at several locations during the experiment. The recorded images were analyzed to calculate the surface wave-length and the wave-height using the imaging technique converting pixel to the metric unit. The presented surface wave describes a single basic wave with amplitude $a\ (= H/2)$, wave number $k\ (=2\pi/L_w)$, and time period T having $ak < 1$, i.e., wave height is small compared to wave-length, which quantifies that the present generated waves are regular 2D waves (Dean and Dalrymple, 2000). The experimental parameters for current-only and combined wave-current flow are shown in Table 1. It is to be noted here that, x the stream-wise coordinate, y the transverse coordinate, z the bottom-normal coordinate and u, v and w are the associated velocity components respectively. Further, $\overline{u}$, $\overline{v}$ and $\overline{w}$ denotes the time-averaged velocity components and u', v' and w' denotes the corresponding velocity fluctuations.

A SonTek down-looking 16 MHz micro-acoustic Doppler velocimeter (Micro-ADV) was mounted on the flume to measure the fluid velocity with fluctuations at 40 Hz over the flat horizontal surface for both current-only and combined wave-current flow. The measurement was carried out at the flume centerline (= 11 m from the last wire mesh where the flow is verified to be fully developed flow) for 5 min duration. The lowest and the highest measurement point from the bed was about 0.40 cm and 14 cm respectively. The time series data recorded by ADV were firstly filtered by removing erroneous values. In fact, the data assessment consisted of (i) visual inspection of plotted time series (ii) estimation of signal-to-noise ratio and correlation samples using Win-ADV software and (iii) velocity spectra. The details of the data assessment based on all three procedures are presented in Singh et al. (2018a).

After the data assessment, the time-averaged velocity was computed at every sampling point by taking mean over the total acquisition time. The instantaneous velocity for combined wave-current flow in stream-wise direction was then decomposed as follow: