Research paper

Waves plus currents crossing at a right angle: near-bed velocity statistics

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ABSTRACT

Wave–current flow over a bottom covered with different roughness elements was analysed to provide new insights into the statistical properties of the near-bed velocity. Experimental data of three different experimental campaigns, with orthogonal waves and currents over a sandy bed, a gravel bed and a rippled bed were used. Velocity profiles were acquired by means of a micro-ADV. The paper focuses on the effects that the waves have on the statistics of the velocity in the current direction. In particular, in the case of a steady current only, the near-bed velocities closely follow a Gaussian distribution. When waves are added, the distribution becomes double-peaked. In order to get single-peaked velocity distributions the total velocity events in the current direction were split in two classes according to the sign of the wave directed velocities. The nature of the distribution functions is influenced by the mass conservation principle and, in the rippled bed case, by the vorticity dynamics.

Keywords: Bed roughness; higher-order statistics; probability distribution function; ripples; wave boundary layer; wave–current interaction

1 Introduction

In shallow coastal waters near-bottom flow is often generated by waves and slowly varying currents, the latter being produced by phenomena such as radiation stress, set-up, tides or other factors. It has been observed that the thin wave boundary layer at the bottom, driven by the oscillating wave orbital velocity, strongly affects coexisting currents (Grant & Madsen, 1979). Indeed, the high shear velocity within the wave bottom boundary layer generates strong turbulence and large bed shear stresses which impact on the current, leading to increased bottom resistance in the presence of combined flows (Lodahl, Fredsøe, & Sumer, 1998). The combined wave–current flow thus plays a fundamental role on the sediment transport, mixing processes, diffusion, and other important coastal phenomena.

Several researchers contributed to the understanding of the physical mechanisms of wave–current interaction, by analysing the combined flow over smooth or rough beds both experimentally or numerically. Most of these studies are focused on the effects on the velocity profile that a wave added to a pre-existing current has on the current velocity profile, particularly within the wave bottom boundary layer.

The effects of waves following or opposing the current over fixed smooth or rough beds have been widely investigated. For example, Simons, Grass, and Mansour-Tehrani (1992) and Simons, Grass, Saleh, and Mansour-Tehrani (1994) analysed the case of waves propagating with or against a current over a fixed layer of sand. They found that the presence of waves induces a significant reduction of the mean flow in the upper part of the water column, and an increase close to the bed. In the case of a current dominated flow due to colinear current and oscillatory flow, Lodahl et al. (1998) observed that a linear interaction between the laminar wave and the current occurs; if the flow is wave dominated, a relaminarization of the steady turbulent flow or an increase of the shear stress may occur, depending on whether the boundary layer is laminar or turbulent. Huang and
Mei (2003) developed a theoretical model to predict the wave influence on a turbulent current over smooth or rough beds. They predicted a velocity increase in the case of waves propagating with the current and a decrease in the case of opposing flows. Recently, Yuan and Madsen (2015) measured the horizontally uniform turbulent wave–current bottom boundary layer flow subject to asymmetric forcing. They found that within the seabed boundary layer flow the magnitude of the mean velocity is larger for opposing than for following waves and current.

In the field, waves and currents may interact at an angle that, in the nearshore region, is often close to $90^\circ$. The experimental and numerical investigation of the interaction of waves and currents superimposed at an angle is much more difficult and far fewer studies exist. Arnskov, Fredsøe, and Sumer (1993) performed experiments on waves and currents interacting at $90^\circ$ over a smooth bed to evaluate the effects of the flow interaction on the bed shear stress. In this case significant nonlinear enhancement of the maximum shear stress was not observed. Andersen and Faraci (2003) used the same experimental set-up with a movable bed to detect the range of wave–current velocities within which bedform geometry could be assumed to be forced only by the oscillatory flow, in order to validate some assumptions in a $\kappa - \omega$ turbulence closure model.

Musumeci, Cavallaro, Foti, Scandura and Blondeaux (2006) investigated the flow produced by waves plus current crossing at a right angle over rough beds. They found that when waves are added onto a current over a bed characterized by a small roughness, an increase of the current flow at the bed occurs; the contrary occurs in the case of large roughness. Orthogonal waves and current over a movable bed were also considered by Fernando, Guo, and Lin (2011), who collected velocity measurements and compared their results with existing literature models for wave–current interaction. They found that an agreement between models and experiments exists only for small to medium wave heights. Lim, Madsen, and Cheong (2012) documented an increase of the angle between the mean flow and the waves due to the presence of wave induced mass transport and a decrease of the hydraulic roughness in combined flows compared to the current alone case. Similar results have been obtained by Lim and Madsen (2016).

Waves plus currents over rippled beds have been investigated, among others, by Ranasoma and Sleath (1994), Mathiesen and Madsen (1996), Fredsøe, Andersen, and Sumer (1999), Faraci, Foti, and Musumeci (2008) and Madsen, Negara, Lim, and Cheong (2010). Ranasoma and Sleath (1994) performed LDA measurements of orthogonal wave–current flow over fixed ripples. Close to the bed they found that, due to the momentum exchange induced by the vortex ejection, measurements do not agree with classical eddy viscosity models. Mathiesen and Madsen (1996) compared the wave roughness with that of a combined flow. They found that in the case of combined flow the roughness is similar to that of a pure wave and a single roughness scale can be considered. By means of both experimental results and a $\kappa - \omega$ turbulence closure model, Fredsøe et al. (1999) found an increase up to one order of magnitude in the bed roughness when waves are superimposed to a current, while Faraci et al. (2008) found that a rippled bed behaves like a macro-roughness for the current, causing the wave boundary layer to become turbulent. Madsen et al. (2010) observed that when wave induced bedforms are at an angle with the current, the near-bottom flow tends to veer parallel to the ripple axis; a dramatic increase of the roughness experienced by a current flowing parallel to the crests of the ripples is also observed when near perpendicular waves are present, due to the nonlinear interaction of the velocity components.

Notwithstanding the large amount of literature on wave–current interaction, attention has been focused almost exclusively on the mean flow, whereas to the knowledge of the authors little has been reported to understand the statistics of the combined flow, which, due to turbulence, fluctuates spatially and temporally around its average values. Nevertheless, a quantitative analysis of the statistical properties of a combined wave–current flow is necessary to understand some aspects of important bed processes, such as erosion and sediment transport. For example, it is known that the threshold of sediment motion is mainly due to the peak velocities of the turbulent flow which destabilizes the bed particles, but it is often referred to the mean shear stress at the bottom. A pioneering work in this context was performed by Grass and Ayoub (1983), who proposed a probabilistic model to interpret turbulence-induced instability of a movable bed. Later on, Parker, Paola, and Leclair (2000) also reported that the implementation of a probabilistic concept in reformulating Exner equation provides a better understanding of the sediment transport at the bed. The importance of using a probabilistic approach to describe the bed characteristics themselves has been also recognized. For example, Nikora, Goring, and Biggs (1998) and Friedrich, Nikora, Melville, and Coleman (2006) used a random field approach to characterize a gravel or a rippled bed as an alternative to the characteristic particle size approach, and found that the gravel bed elevation is distributed as a Gaussian-like variable, while the coupling of skewness and flatness values allows different kinds of bedforms to be distinguished.

Although the characterization of the flow is desirable, as pointed out by Cheng (2006), the majority of the works dealing with sediment transport problems take into account turbulence only through time averaged velocities or shear stress. Among the few studies which have shed light on the properties of turbulence, Kim, Moin, and Moser (1987) performed a direct numerical simulation of a turbulent channel flow in the presence of smooth walls, to obtain quantitative information on turbulence structure. Recently, time resolved PIV techniques have been employed by Willert (2015) for estimating flow statistics, spectra, probability density functions and correlations of a turbulent boundary layer in a wind tunnel. However none of the previously mentioned works deal with combined wave–current flows.
In order to contribute to the characterization of this type of flow, the present work presents an analysis of both low-order and high-order statistics of the velocity field generated by superimposing a regular wave field to an orthogonal current. In order to understand the role played by the bed roughness, three different fixed bottom conditions are considered, namely a sandy bed, a gravel bed and a rippled bed. The present analysis is performed using an existing experimental dataset (Faraci et al., 2008; Musumeci et al., 2006), acquired by the authors but never analysed from this perspective. In particular, this study is focused on the influence of the waves on the current properties. The distribution functions of the velocity in the current direction, considering both the velocity and the turbulent fluctuations, are discussed. Moreover, since it is recognized that the wave phase plays a major role on the modification of the current, the effects of the combined flow on the phase-averaged flow are also presented.

The paper is organized as follows: first the experimental set-up and procedure are presented, then experimental data are discussed in Section 3 and the conclusions are presented in Section 4.

2 Experimental campaign

2.1 Experimental set-up and procedure

The experiments were carried out at the Hydraulic Laboratory of the University of Catania in a wave flume equipped with a recirculating system which allows a uniform current to enter the flume at a right angle with respect to the direction of wave propagation.

The wave flume is 18.00 m long, 4.00 m wide and 1.20 m deep. Regular and irregular waves can be generated by a flap type wavemaker, which is driven by an electronically controlled pneumatic system. Opposite the wavemaker a porous plane type wavemaker, which is driven by an electronically controlled recirculating system which allows a uniform current to enter the flume at a right angle with respect to the direction of wave propagation.

The current is driven by a submerged 11.0 kW electropump, with a maximum discharge of 0.25 m$^3$ s$^{-1}$; it flows within a series of channels, in order to dampen turbulence, and it enters the wave flume at a right angle. The current inlet is 2.5 m wide, the outlet is perfectly symmetric to the inlet. The corners of the inlet and of the outlet are shaped in such a way as to minimize effects of wave diffraction on the current within the measurement area. Additionally, passive wave absorbers at the outlet walls minimize spurious wave reflections.

Three different types of bed roughness have been considered in the central part of the wave flume, covering an area of 3.5 m $\times$ 4 m. During the first campaign, referred to as sandy bed (SB), a single layer of fine quartz sand characterized by a $D_{50}$ of 0.24 mm was glued onto the bed; during the second campaign, referred to as gravel bed (GB), a single layer of marble stones with a median grain size of $D_{50} = 30$ mm was glued on the bed to simulate a gravel bed. These two campaigns have been extensively described in Musumeci et al. (2006). Finally the third campaign, referred to as rippled bed (RB), was carried out by covering the bed with a fixed 2D PVC rippled panel, made up by a unique contoured block. The regular ripple height was 1.85 cm and ripple length was 12.5 cm. The bedform dimensions were chosen to be in agreement with the characteristics of ripples generated during the experimental campaign performed by Andersen and Faraci (2003), in the presence of orthogonally superimposed waves and currents characterized by the same ratio between current velocity and wave orbital velocity as the ones used in the present work. In particular, it was found that the considered bedform characteristics correspond to waves having periods between 1 and 1.4 s and heights of about 0.1 m, propagating over a depth of about 0.3 m. The detailed experimental data of the RB campaign have been reported in Faraci et al. (2008).

For each type of bed roughness, three different types of flows have been generated: wave-only, current-only and waves plus currents. The surface elevation was measured by means of several resistance wave gauges located along the flume. Moreover, a Sontek micro acoustic Doppler velocimeter (micro-ADV), mounted on a movable carriage, was used to measure the three velocity components. The sampling volume is a cylinder 9 mm high and having a volume of 0.3 cm$^3$, located 5 cm below the transmitter. Due to the dimensions of the measuring volume, the point which is closest to the bed was located about 0.45 cm above the bottom. Thus velocity measurements were not gathered either within the thin wave bottom boundary layer (O(∼ 1 mm)), and in the region between wave crest and 5 cm below wave trough. The adopted sampling frequency was 30 Hz.

In Musumeci et al. (2006) a detailed report on the spatial homogeneity of the wave–current interaction in the central part of the channel is reported. Within this area a single measurement station located along the mid line of the current stream, 2.5 m far away from the inlet, has been considered for the SB and GB campaigns. For the RB campaign five measuring stations were considered along the ripple profile, two of them at the two adjacent crests, one at the trough and the other two between crest and trough (Fig. 1b). Each velocity time series was acquired for ≈ 60 wave cycles. In order to verify that the sampling time was long enough, it was ascertained that the standard deviation of the current velocity component was stable. In Table 1 this quantity is reported for the point which is closest to the bed in the gravel bed roughness case and for a wave plus current condition. Here it is shown that even though the acquisition has been performed for a longer time period (75 cycles), convergence can be considered to be reached after 60 cycles. Each velocity profile was obtained collecting about 10–15 points at each station along the water column.

Figure 1 reports a sketch of the wave plus current experimental flume where the two orthogonal interacting flows are highlighted. Figure 1 shows also the reference system, where
Table 1 Convergence test. SB, \( V_{DA} = 0.067 \text{ m s}^{-1} \); \( H = 0.085 \text{ m}; T = 1 \text{ s} \)

| No of cycles | \( V_x \) standard deviation (cm s\(^{-1}\)) | \( V_x \) skewness | \( V_x \) flatness |
|--------------|---------------------------------|----------------|----------------|
| 40           | 0.7533                          | 0.0331         | 2.8443         |
| 60           | 0.7894                          | 0.0875         | 2.9123         |
| 75           | 0.7890                          | 0.0858         | 2.9473         |

x is along the steady current direction, y is along the direction of the wave propagation, z is positive upward and the origin is located at the bottom in the flat bed experiments (SB and GB) and at the trough level in the rippled bed (RB) tests.

The experimental procedure can be summarized as follows:

1. a regular wave motion is generated until steady conditions are reached;
2. wave characteristics and velocity profiles are gathered at the measuring stations;
3. after stopping the wavemaker and fixing the discharge, the recirculating system is run until the water levels in all the channels are stable and a uniform current is established within the wave tank;
4. current only velocity profiles are acquired;
5. waves are superimposed to the existing current and wave current velocity profiles are acquired after steady conditions are reached.

Steadiness of the flow was checked by monitoring mean levels in all the channels; in the presence of currents it was usually reached after 2–3 h after starting the apparatus.

2.2 Experiments

Three sets of experiments, previously referred to as SB, GB and RB campaigns, are discussed here. Wave conditions in all the experiments are characterized by periods between 0.8 and 1.6 s and two different wave heights, namely 0.085 and 0.105 m. Water depth \( D \) is kept constant during all the tests and equal to 0.3 m, while three different values of depth averaged current velocities \( V_{DA} \) are considered, namely 0.045 , 0.067 and 0.100 m s\(^{-1}\). Current only, wave only and wave plus current flow conditions have been considered.

Table 2 reports a summary of the experimental conditions, where the X mark within the bottom roughness columns indicates a performed test. For each test the vertical profiles of the three velocity components, \( V_x, V_y \) and \( V_z \) in the \( x, y \) and \( z \) directions have been acquired.

3 Analysis of experimental data

The analysis of the experimental data is carried out here in order to provide information on the statistics of the velocity component \( V_x \) in the direction of the current. In general such a velocity component, as well as the other ones, can be presented as the sum of two terms:

\[
V_x = \langle V_x \rangle + v_x'
\]  (1)

where \( \langle V_x \rangle \) is the ensemble averaged velocity, and \( v_x' \) is the turbulent fluctuating velocity. The ensemble average can be further
Table 2: Experimental conditions in the presence of a sandy bed (SB), gravel bed (GB) and rippled bed (RB)

| Type | \(V_{DA} \text{ (m}^3\text{ s}^{-1})\) | \(H \text{ (m)}\) | \(T \text{ (s)}\) | SB | GB | RB |
|------|----------------------------------|----------------|--------------|-----|-----|-----|
| CO   | 0.045                            | –              | –            | X   | X   | X   |
| CO   | 0.067                            | –              | –            | X   | –   | X   |
| CO   | 0.100                            | –              | –            | X   | X   | X   |
| WO   | –                                | 0.085          | 0.80         | X   | X   | X   |
| WO   | –                                | 0.085          | 1.00         | X   | X   | X   |
| WO   | –                                | 0.085          | 1.20         | X   | X   | X   |
| WO   | –                                | 0.085          | 1.40         | X   | X   | X   |
| WO   | –                                | 0.085          | 1.60         | –   | –   | X   |
| WO   | –                                | 0.105          | 0.80         | X   | X   | X   |
| WO   | –                                | 0.105          | 1.00         | X   | X   | X   |
| WO   | –                                | 0.105          | 1.20         | X   | X   | X   |
| WO   | –                                | 0.105          | 1.40         | X   | X   | X   |
| WO   | –                                | 0.105          | 1.60         | –   | –   | X   |
| WC   | 0.045                            | 0.085          | 0.80         | X   | X   | X   |
| WC   | 0.045                            | 0.085          | 1.00         | X   | X   | X   |
| WC   | 0.045                            | 0.085          | 1.20         | X   | X   | X   |
| WC   | 0.045                            | 0.085          | 1.40         | X   | X   | X   |
| WC   | 0.045                            | 0.085          | 1.60         | X   | X   | X   |
| WC   | 0.045                            | 0.105          | 0.80         | X   | X   | X   |
| WC   | 0.045                            | 0.105          | 1.00         | X   | X   | X   |
| WC   | 0.045                            | 0.105          | 1.20         | X   | X   | X   |
| WC   | 0.045                            | 0.105          | 1.40         | X   | X   | X   |
| WC   | 0.045                            | 0.105          | 1.60         | –   | –   | X   |
| WC   | 0.067                            | 0.085          | 1.00         | X   | X   | X   |
| WC   | 0.100                            | 0.085          | 1.00         | –   | X   | –   |

Note: CO, current only; WO, wave only; WC, wave plus current.

decomposed into two terms as shown below:

\[
\langle V_x \rangle = \bar{V}_x + \tilde{v}_x
\]  

where \(\bar{V}_x\) is the time averaged velocity and \(\tilde{v}_x\) is the oscillating velocity having a period equal to the wave period. The ensemble average has been evaluated by phase-averaging the velocity measurements. It is worth pointing out that in the acquired time series there was no evidence of spurious spikes, because the fluctuating velocities never exceed \(\pm 2\) times the standard deviation of the measured component; therefore a pre-processing of the velocity time series was not needed. An example is shown in Fig. 2, where the three components of the acquired signal are shown (Fig. 2a) along with the decomposition of \(V_x\) into the time-averaged velocity \(\bar{V}_x\), the oscillating velocity \(\tilde{v}_x\) and the fluctuating component \(v'_x\) for a test case characterized by a depth averaged velocity \(V_{DA} = 0.045 \text{ m s}^{-1}\), a wave height \(H = 0.085 \text{ m}\) and a wave period \(T = 1.6 \text{ s}\) (Fig. 2b).

Part of the statistical analysis of the near-bed flow reported in the following is carried out in terms of probability density function of the near-bed velocity. This function provides unique information about the distribution of a given variable and it can be used to compute all the relevant statistics of a turbulent flow. When a current interacts with orthogonal waves, the probability density of the current velocity is modified by the waves themselves. Knowledge of this interaction process and how it affects the probability density of the velocity fluctuations is relevant not only for the hydrodynamics but also for the sediment transport.
transport. Indeed, wave–current interactions usually occur over a bed made up of loose materials that can be mobilized by an increase of the velocity fluctuations.

In Section 3.1 the frequency distribution of $V_x$ at a fixed location close to the bottom is analysed. Section 3.2 is devoted to the analysis of the distribution of the turbulent component $v'_x$, moreover the vertical profiles of the statistics for both the current only case and the wave plus current cases are compared. Finally in Section 3.3 the analysis of the phase-averaged velocity component $V_x$ is presented and discussed.

### 3.1 Statistical analysis of total near-bed velocity

The statistics of the velocity component in the $x$ direction are analysed here. The frequency distribution of the bed velocity has been obtained by counting the number of occurrences $N^*$ in $n$ classes of $V_x$ and by obtaining the relative number of occurrences $N$ as the ratio between $N^*$ and the product between the class amplitude and the total number of occurrences. Here the number of classes $n$ has been chosen equal to 40, because such a value is sufficiently high to provide a good representation of the whole velocity distribution but still adequate to contain enough events in each class.

Figure 3 shows the probability distribution of one of the current only cases ($V_{DA} = 0.045 \text{ m s}^{-1}$) at the measuring point located closest to the bed, i.e. at about 0.5 cm above it; each plot corresponds to a different roughness condition, i.e. SB, GB and RB respectively. It can be observed that in the case of sandy bed the PDF is symmetric and the skewness is approximately zero. In the gravel and rippled bed cases the behaviour is rather similar to each other and the distributions negatively skew. This implies that the number of negative fluctuations is larger compared to that of the positive ones.

Similarly, in Fig. 4 the probability distributions for different currents ($V_{DA} = 0.045, 0.067$ and $0.100 \text{ m s}^{-1}$) are shown. The distributions are all rather symmetric and closely follow the Gaussian PDF. As expected, as soon as the current velocity increases, the distribution becomes flatter and broader as a result of the increased turbulence.

When waves are added on the existing current, the flow shows a much more complex behaviour. In Figs 5–7 the PDF of a SB, a GB and a RB roughness condition respectively for different wave plus current flows are reported. In all the figures the depth averaged velocity of the current is equal to $V_{DA} = 0.045 \text{ m s}^{-1}$; this current has been superimposed to four wave conditions with two different wave periods (namely 0.8 and 1.4 s) and two different wave heights (0.085 and 0.105 m). The differences between the frequency distribution of the current velocity and the Gaussian probability density function increase as the period increases. In particular two main peaks are visible; in the rippled bed tests (Fig. 7), where the measurement point is located in the bedform trough and thus sheltered by the ripple lee side, such a feature turns out to be less apparent for smaller wave heights. In general, the discrepancies with the normal distribution increase with the wave period, while the wave height does not play a significant role. Similar features, not shown here for sake of brevity, have been observed also for intermediate wave periods ($T = 1$ and $1.2$ s). This behaviour is due to an oscillatory flow induced by waves also in the current direction. One of the main mechanisms through which the velocity in the current direction fluctuates is due to the advection of $x$-momentum along the vertical due to the vertical gradient of the mean current velocity. In the convective term of the Navier–Stokes equations, this advection is provided by the term $V_z \partial V_x / \partial z$ where $V_z$ is the vertical velocity which is largely due to the wave orbital motion. The effect of this term on the current velocity can be illustrated by the equation $\partial V_x / \partial t = -V_z \partial V_x / \partial z$, which neglects several other terms. Although this equation represents only a rough approximation of the real phenomenon as it neglects several terms, it is sufficient to qualitatively explain the oscillating behaviour of the current velocity. The right hand side of the previous equation is nonlinear, therefore it is not easy to obtain rigorous information about the phase of oscillation induced by itself. If at first it is assumed that $\partial V_x / \partial z$ does not vary too much during the wave period and that it is positive, we observe that according to the previous equation the time derivative of the current velocity is positive when the vertical velocity is negative and vice versa. The reasonableness of this result can be noted in Fig. 2 where the time development of the velocities along the three Cartesian axes is shown. It can be observed that most of the times when $V_z$ is positive the time derivative of the current velocity is negative, and vice versa. Thus if the vertical velocity oscillates like $\sin(\sigma t)$ the current velocity oscillates as $\cos(\sigma t)$. This process occurs along the entire water column; however, due to the exponential orbital velocity decay over the vertical, it is more apparent only for larger waves, whose effect penetrates down to the bottom. Of course the neglected terms in the previous equation and the nonlinear effect due to the time variation of the vertical gradient of the current velocity, make the picture a little different from the one described above. Another effect contributing to the oscillating behaviour of the current velocity is the time variation of the water depth. In particular, under the wave crest the total water depth is larger, inducing a decrease of velocity with respect to its mean value. Conversely, under the wave trough the total water depth is smaller, resulting into an increase of the velocity and a consequent peak for $V_x$ larger than the mean value.

The two peaks of the PDF that can be observed in Figs 5b–d, 6b–d, 7b–d are due to the velocities occurring around the maximum and the minimum of the oscillating current velocity (as shown in Fig. 2). This result is similar to that occurring with a sinusoidal function which has a PDF with two peaks of the same magnitude, one peak is located at the maximum and the other at the minimum. In the present case however the shape of the function is not exactly sinusoidal, thus the two peaks of the PDF are different.

According to the previously mentioned processes, the $V_x$ data have been split into two classes of current velocities, the first
Figure 3  Frequency distribution of $V_x$ in the current only case at a point 0.5 cm far from the bed; $V_{DM} = 0.045 \text{ m s}^{-1}$ and different bed roughness: (a) SB; (b) GB; (c) RB (trough). A Gaussian PDF is also superimposed.

Figure 4  Frequency distribution of $V_x$ in the current only case at a point 0.5 cm far from the bed; RB and different $V_{DM}$: (a) 0.045 m s$^{-1}$; (b) 0.067 m s$^{-1}$; (c) 0.100 m s$^{-1}$. A Gaussian PDF is also superimposed.

Figure 5  Frequency distribution of $V_x$ in the wave plus current case at a point 0.5 cm far from the bed for SB bed roughness, $V_{DM} = 0.045 \text{ m s}^{-1}$ and different wave conditions: (a) $H = 0.085 \text{ m}$, $T = 0.8 \text{ s}$; (b) $H = 0.085 \text{ m}$, $T = 1.4 \text{ s}$; (c) $H = 0.105 \text{ m}$, $T = 0.8 \text{ s}$; (d) $H = 0.105 \text{ m}$, $T = 1.4 \text{ s}$. A Gaussian PDF is also superimposed.
corresponding to positive values of the wave velocity component (i.e. to the passage of a wave crest, or onshore directed wave velocities \(V_y^+\)), hereinafter referred to as \(V_y^+\), and the second corresponding to negative values of the wave velocity component (i.e. to the trough passage, or offshore directed wave velocities \(V_y^-\)) hereinafter referred to as \(V_y^-\). The same
decoupling procedure can also be applied in order to obtain the quantities \( V_z^{+} \) and \( V_z^{-} \), corresponding respectively to current velocities occurring simultaneously to a positive (upward) or negative (downward) vertical velocity. Several probability density functions have been determined for the two classes of data.

The PDFs of \( V_z^{+} \) and \( V_z^{-} \) are shown in Fig. 8 for \( V_{DA} = 0.045 \text{ m s}^{-1}, H = 0.085 \text{ m}, T = 1.2 \text{ s} \). It is possible to observe that for all the roughness conditions, \( V_z^{+} \) and \( V_z^{-} \) distributions are rather separated one from the other, and the peak of the PDF of \( V_z^{+} \) always occurs at smaller velocities than that of \( V_z^{-} \).

Indeed, as mentioned, in the presence of the combined wave–current flow, according to the mass conservation principle, velocity in the current direction should be decreased under the wave crest and increased under the wave trough. Hence, the peak of the \( V_x \) velocity should be 180° out of phase compared to \( V_y \), while, due to vertical advection of \( x \)-momentum described by the term \( V_x \partial V_z / \partial z \) in the Navier–Stokes equations, a phase shift may occur. Assuming that the effects of the continuity are more significant than the other ones, the decoupling by using the sign of \( V_y \) should be the most significant one. However, as a result of the above effects, the oscillation of \( V_x \) may be phase-shifted with respect to \( V_y \). It follows that the separation of the peaks of the PDF at higher or lower velocities is not exact, as shown in Fig. 8a and b, for the SB and GB conditions.

Moreover, as for the current only case, the PDF is rather flat for the GB case and sharper for SB and RB tests, where the standard deviation is smaller. This difference is a macroroughness effect and can be attributed to the fact that the gravels are larger and randomly positioned onto the bed. This affects the level of turbulence within the boundary layer, by spreading the near-bed velocities over a wide range of values.

In Fig. 9a the separation distance between the two peaks of the PDF is plotted against the wave period \( T \) for the SB case. In the plot data characterized by two different wave heights are shown. Such a distance has been evaluated as the difference between the mean values of the two Gaussian PDFs that describe the two classes of current velocities, the first one corresponding to positive values of the wave velocity component, the second one corresponding to negative values of the wave velocity component, as it will be better detailed in the following. Such a distance increases for increasing \( T \). As a matter of fact, the presence of the double-peak distribution indicates the existence of an oscillating flow, induced by the presence of the waves, also in the current direction. As a consequence of this, the distance between the two peaks \( \Delta V_x \) is larger for higher wave heights.

The standard deviation of the two different PDF \( \sigma V_x^{+} \) and \( \sigma V_x^{-} \), obtained as described above, is plotted in Fig. 9b, as a function of the wave period. The results indicate that the standard deviation tends to increase with the wave period as well. Such an increase seems to be independent both on the wave phase and on the intensity of the current, demonstrating that as the wave orbital motion is more intense at the bed, the fluctuations of the current velocity increase in the same way both under the wave crests and the wave troughs. It turns out that shallower water waves should play a major role on the increase of turbulent fluctuations at the bed.

In Figs 10 and 11 the attention is focused on the rippled bed case: the previously described procedure has been applied to determine the PDF of \( V_x^{+} \) and \( V_x^{-} \) and the PDF of \( V_y^{+} \) and \( V_y^{-} \) respectively. In Figs 10a and 11a the measurement point...
Figure 9 (a) Variation of $\Delta V_y^x$ as a function of $T$; (b) Variation of $\sigma V_y^x$ as a function of $T$. SB tests for $V_{Da} = 0.045 \text{ m s}^{-1}$

Figure 10 Frequency distribution of $V_y + x$ and $V_y - x$ for the rippled bed case: (a) intermediate between crest and trough; (b) trough; (c) intermediate between trough and crest; (d) crest. The measuring point is located 0.5 cm far from the bottom. Same test conditions and symbols as in Fig. 8. Black and white bar plot: current velocities acquired during the passage of negative wave velocities ($V_y^-$). Grey bar plot: current velocities acquired during the passage of positive wave velocities ($V_y^+$). The corresponding Gaussian PDFs are also superimposed.

is located at an intermediate position between the offshore ripple crest and the trough (point 2 with reference to the sketch in Fig. 1); in 10b and 11b the point is located at the trough (point 3), then in Figs 10c and 11c the second intermediate point is considered (point 4) and finally Figs 10d and 11d report measurements gathered at the onshore crest (point 5). Only the onshore crest has been plotted as the results obtained at points 1 and 5 are in good agreement.

Looking at these two figures, at first glance one may notice that the behaviour of $V_y^+$ and $V_z^+$ as well as the one of $V_y^-$...
Figure 11 Frequency distribution of $V_z^+ + V_x$ and $V_z^- - V_x$ for the rippled bed case: (a) intermediate between crest and trough; (b) trough; (c) intermediate between trough and crest; (d) crest. The measuring point is located 0.5 cm far from the bottom. Experimental test conditions as in Fig. 8. Black and white bar plot: current velocities acquired during the passage of negative vertical velocities ($V_z^-$). Grey bar plot: current velocities acquired during the passage of positive vertical velocities ($V_z^+$). The corresponding Gaussian PDFs are also superimposed.

and $V_z^-$ is slightly similar. In particular, at the first intermediate point (point 2, Figs 10a and 11a) the two distributions are unexpectedly roughly superimposable. This evidence has been related to the vorticity dynamics at the rippled bed. Indeed, as shown by Faraci et al. (2008), under the wave crest, the leeward side is affected by a high clockwise vorticity generated by the vortex shedding at the ripple crest. It follows that water particles coming from the accelerated seaward side are pulled down in the leeward side by the vortex generated by flow separation. Since these fluid particles come from a region farther from the bed, where the velocity is large, around the crest phase an increase of $V_z$ occurs which partially compensates the decrease of the velocity determined by the crest passage, as described also in Section 3.3. Therefore this mechanism leads to levelling the values of $V_z^+$ and $V_z^-$ (or $V_x^+$ and $V_x^-$).

Similarly, at the second intermediate point (point 4, Figs 10c and 11c), under the wave trough, high vorticity pulls down the fluid coming from higher velocity regions, leading to an increase of $V_z^-$ with respect to $V_x^+$, thus at point 4 the two distributions are more separated than at point 2. Both ripple crest and trough are less affected by such a mechanism as the vorticity is smaller there.

Under the wave crest, at all the ripple locations, the current velocities are more peaked around the mean value than under the wave trough. This depends on the wave shape, which is indeed characterized by narrow and high crests and flat and broad troughs, which last more than one half period. Such evidence is also confirmed by observing that the sum of occurrences of $V_z^-$ is always larger than that of $V_z^+$.

In Fig. 12 the modification of the mean flow direction as a consequence of the wave superposition on the existing current is shown. For the sake of completeness the mean flow is also shown here, even though the results have been already discussed in Musumeci et al. (2006) and Faraci et al. (2008). Figure 12a and d concern the SB case, Fig. 12b and e the GB case, and Fig. 12c and f the RB case. The angle $\theta = 0^\circ$ corresponds to the current alone propagation direction (Fig. 1c). When waves are added to the current, in the case of SB roughness the mean angle veers about $-10^\circ$, as a consequence of the undertow current resulting from the wave propagation. This result is in very good agreement with the experimental observations of Lim and Madsen (2016). When a rippled bed or a gravel bed is considered, the veering shows different features. Indeed, close to the bed the current veers towards the beach up to $5^\circ$, then $\theta$ decreases quite abruptly up to $-25^\circ$ at about $z = 2$ cm. At this depth the local effects due to the roughness are transferred onto the mean flow, with an overall increase of the veering angle. Lim and Madsen (2016) interpret such a process as a consequence of turbulence asymmetry and mean momentum transfer. The decrease of the veering angle in the GB and RB cases is due to the set-up of an offshore directed streaming near the bed, generated by the asymmetry in the wave shape and the large turbulent fluctuations induced by the large roughness that characterizes these two cases (Scandura, Faraci, & Foti, 2016).
the upper part of the measured water column in the SB case the veering angle tends to increase due to the closeness of the water surface, as also observed in Lim and Madsen (2016). In the GB and RB cases the opposite occurs: indeed, \( \theta \) tends to line up to \( \approx -18^\circ \). The results of Lim and Madsen (2016) in the case of rough bed are in substantial agreement with the present findings. However it is worth pointing out that they do not observe the inversion of veering angle close to the bed probably because they did not measure within the 2 cm closest to the bed.

### 3.2 Statistical analysis of turbulent fluctuations

The statistics of the turbulent fluctuations \( v'_x \), as described in Eq. (1), are presented here. Figure 13 shows the probability distribution for the wave plus current condition characterized by \( V_{DA} = 0.045 \text{ m s}^{-1}, H = 0.105 \text{ m}, T = 1.2 \text{ s} \), for the three bottom roughness cases SB, GB and RB respectively. It can be noted that such a component behaves differently from \( V_x \). Indeed, in the PDF there is no evidence of double peaks. This is mainly due to the fact that \( v'_x \) does not contain the fluctuating velocity induced by the wave motion, although this motion affects the turbulent component, as will be shown in the following. Figure 13 also shows that the probability distribution is rather well described by the Gaussian distribution, especially for sand and rippled bed cases. It can be noted that the largest turbulent fluctuations are of about 5 cm s\(^{-1}\), higher than the current depth averaged velocity.

A measure of the width of the probability distribution is provided by the standard deviation of the velocity fluctuations, defined as \( \left(\frac{\sum v'_x^2}{n}\right)^{1/2} \). Figure 14a and b shows the vertical profiles of the standard deviation for the current only tests shown in Figs 3 and 4 respectively.

In Fig. 14a the standard deviation for the sand bed case is larger than in the ripple bed case but the largest values are obtained for the gravel bed because of the large element roughness. Although in the RB case the roughness is also large, since the current flows parallel to the ripple crests, it does not significantly affect the turbulence intensity. The vertical distribution of the standard deviation shows that turbulence is much more intense close to the bed. It decreases with \( z/D \) up to a certain elevation \( z^* \), beyond which it shows rather constant values. In particular, in Fig. 14a it can be observed that \( z^* \) is equal to about 0.2–0.25 for both the SB and the RB tests, whereas for the gravel bed case \( z^* \) is larger (\( z^* = 0.35 \)) because the large random roughness of the gravel bed (GB) produces an intense turbulence which extends over a larger portion of the water column.

For the rippled bed case shown in Fig. 14b the effect on the standard deviation of varying the current velocity is also shown. Even in this case values are higher close to the bed and then tend to reach a constant value of about 0.6, 0.75 and 0.9 for \( V_{DA} \), respectively equal to 0.045, 0.067 and 0.100 m s\(^{-1}\). However, the level beyond which such values are achieved remains similar to that of the previous case (\( z^* = 0.25 \)).

Figure 14c shows the standard deviation for waves plus current conditions having current characteristics equal to those of Fig. 14a and a wave with \( H = 0.085 \text{ m s}^{-1} \) and \( T = 1.2 \text{ s} \). Adding an orthogonal wave to a current causes a large increase of the standard deviation of the turbulent fluctuations. Close to the bottom, for both ripple and sand bed cases, the standard deviation increases from about 0.8 for the current only case up to about 1.2 for the waves plus current. For the gravel bed, close to the bottom the standard deviation doubles the value due to the current only.

Figure 15 shows the trend of the Reynolds stress \( \overline{v'_x v'_z} \) along the depth for the current only condition characterized by \( V_{DA} = 0.045 \text{ m s}^{-1} \) and for the wave plus current condition obtained by superimposing a wave having \( H = 0.085 \text{ m} \) and \( T = 1.2 \text{ s} \) on the previous current and considering the three different types of bed. Near the bottom the magnitude of the Reynolds stress for the gravel bed is much larger than that of the other two types of bed roughness. On the other hand the magnitudes of the Reynolds stress of the SB and of the RB cases are close to each other, but that of the sand is slightly larger than the other one. In the wave plus current case (Fig. 15b) the magnitude of the Reynolds stress increases with respect to the current only case. Generally it is larger for the gravel bed case, except near the bed where the Reynolds stress is similar for all three cases. It is mostly negative along the depth as it generally occurs for a steady turbulent current. In the current only case it reaches its minimum value at an elevation \( z/D \approx 0.08 \) for all the roughness conditions, while the minimum value changes depending on the bed condition. In the wave plus current case its value close to the bed is similar to the current only case, while it further decreases at an elevation \( z/D \approx 0.2 \). However, in the upper part of the water column for all the conditions the Reynolds stress tends to increase and for the sand bed case it becomes even positive.

In Fig. 16 the skewness \( S = \overline{v'_x^3/\left(\overline{v'_x^2}\right)^{3/2}} \) and the flatness \( F = \overline{v'_x^4/\left(\overline{v'_x^2}\right)^2} \) factors of the current velocity are shown versus the bottom distance, made non-dimensional by means of the water depth \( D \). The skewness is a measure of the asymmetry of the probability density function with respect to the average value \( \overline{v'_x} \). For symmetric distributions with respect to \( \overline{v'_x} \), the skewness vanishes; an example of this behaviour is represented by the normal distribution. When the skewness is negative the largest fluctuations of \( v'_x \) are negative; the opposite occurs if the skewness is positive. The flatness provides a measure of the peakedness of the probability density function. In particular, the flatness is equal to 3 in the case of a normal distribution. In the present analysis, in the current only case the skewness has small values very close to the bed, then it decreases reaching values of \( -0.3 \) to \( -0.4 \) far from the bed. The flatness assumes values close to 3 near the bed, then it falls below 3 for 0.02 < \( z/D < 0.15 \) and finally it increases, attaining values of about 3.5. These results show that a region close to the bottom exists where the skewness is small and the flatness is close to 3, thus explaining why in Fig. 13 the frequency distribution is well described by a Gaussian distribution.
Figure 12 Mean flow (a, b, c) and angle of mean flow (d, e, f) for current alone and wave plus current flow for different roughness conditions. $V_{DA} = 0.045 \text{ m s}^{-1}$; $H = 0.085 \text{ m}$; $T = 0.8 \text{ s}$: (a, d) SB; (b, e) GB; (c, f) RB

Figure 13 Frequency distribution of turbulent fluctuations $v_x'$ in the wave plus current case at a point 0.5 cm far from the bed; $V_{DA} = 0.045 \text{ m s}^{-1}$; $H = 0.105 \text{ m}$; $T = 1.2 \text{ s}$ and different bed roughness: (a) SB; (b) GB; (c) RB (trough). A Gaussian PDF is also superimposed

Similar results were also numerically found by Kim et al. (1987) for a turbulent channel flow at low Reynolds numbers. These results are also superimposed on both graphs, showing a trend similar to the present ones for the different kinds of roughness. A similar analysis was also performed by Willert (2015) in a wind tunnel in the presence of grid-generated turbulence.

In Fig. 17 the skewness and flatness of the fluctuating component $v_x'$ for a wave plus current case characterized by $V_{DA} = 0.045 \text{ m s}^{-1}$, $H = 0.105 \text{ m}$ and $T = 1.2 \text{ s}$ are shown for all the roughness conditions. Differently from what happens in the current only case, the skewness is mainly positive in the lower part of the water column for most of the measured points in the case of sandy and gravel bed, while it changes sign in the upper part of the measured column. In the rippled bed case it remains close to zero for most of the points, showing a slightly positive skewness in the upper part of the measured region. The flatness is rather similar for all the three roughness conditions. It takes large values near the bottom, while at high elevations from the bed it assumes values close to 3. However, at some higher elevations the flatness may be much larger than 3 for the sand bed. On the basis of the results shown in Fig. 17, close to the bed the distribution is far from a Gaussian distribution in the gravel and rippled bed cases, while it follows better the normal distribution in the sand bed case. This is also confirmed by the results on the $v_x'$ distributions shown in Fig. 13, where in the GB and RB cases the peakedness is much higher than the normal one. The normal distribution may be attained far from the bed when the skewness is close to zero.

3.3 Analysis of phase-averaged quantities

The analysis of phase-averaged velocities has been performed in order to show how the velocity in the current direction varies...
Waves plus currents crossing at a right angle

Figure 14  Vertical profile of the standard deviation of $V_x$ for (a) test cases as in Fig. 3; (b) RB roughness condition and different $V_{DA}$ as in Fig. 4; (c) different roughness and waves plus currents as in Fig. 8

Figure 15  Reynolds stresses of: (a) current only flow and (b) wave plus current flow. $V_{DA} = 0.045$ m s$^{-1}$; $H = 0.085$ m; $T = 1.2$ s

Figure 16  Vertical profile of skewness and flatness factors for SB, GB and RB (trough) beds. Experimental conditions as in Fig. 3
Figure 17 Skewness (a) and flatness (b) of the fluctuating component $v'_x$. $V_{DA} = 0.045 \text{ m s}^{-1}; H = 0.105 \text{ m}; T = 1.2 \text{ s}$

Figure 18 Analysis of phase averaged wave plus current flow (a) $\pi/4$; (b) $\pi/2$; (c) $3\pi/4$; (d) $\pi$; (e) $5\pi/4$; (f) $3\pi/2$; (g) $7\pi/4$; (h) $2\pi$. Experimental conditions as in Fig. 8 during the cycle due to the superposition of an orthogonal wave with the current. In Fig. 18 the phase-averaged current-directed velocity profiles acquired along the water column are plotted at eight different instants within the wave cycle, namely $\phi = \pi/4$, $\pi/2$, $3\pi/4$, $\pi$, $5\pi/4$, $3\pi/2$, $7\pi/4$ and $2\pi$. Phase equal to zero corresponds to the zero-upcrossing wave. In each subplot the SB, GB and RB (at the trough) tests with a depth averaged velocity $V_{DA} = 0.045 \text{ m s}^{-1}$, a wave height $H = 0.085 \text{ m}$ and a period $T = 1.2 \text{ s}$ are reported. Close to the bed, SB, GB and RB data show some differences: indeed, when the bottom is rough (GB) the velocity gradient close to the wall is smaller, probably as a consequence of the larger resistance generated at the bottom by the macro-roughness in the presence of the waves. The SB tests, due to the very small bed roughness, independently of the considered phase, exhibit the largest near-bottom velocity gradient; overall, close to the bed the RB tests show velocities similar to those of the SB tests, apart from the case $\phi = 3\pi/2$ and $\phi = 7\pi/4$, where the RB case shows the largest near-bed velocity. At higher elevations, the RB velocity profiles are similar to those of the SB case; however, when the velocities attain the
maximum values ($\phi = 3/4\pi \div \pi$), there is a large difference between them. At all the phases the RB profiles show a strong velocity gradient near the bed, that at an elevation comparable to the ripple height, abruptly decrease. The constancy of the velocity profiles in the rippled bed case for $2cm < z < 16cm$ can be explained by the vertical transfer of momentum due to the vortices ejected at the ripple crests that tend to homogenize the velocity profiles. This occurrence was already observed by Faraci et al. (2008), who pointed out that far from the bed ripples behave like a macro-roughness, due to the strong turbulence associated to the high vorticity released at the ripple crests.

The GB profiles close to the bed exhibit negative velocities at all the accelerating phases. Such behaviour has been noticed in all the GB tests, thus excluding the possibility that this effect could be due to local disturbances. Further analyses are still needed in order to explain such phenomenon.

In general the velocity profiles exhibit a significant variability in relation to the phase, reaching the minimum value close to a phase equal to $\pi/3$, and the maximum value at $1.47\pi$. This result is in agreement with the mechanism responsible for the time variability of the current velocity described in Section 3.1, according to which the minimum of $V_x$ should fall close to the wave crest and the maximum close to the wave trough.

When the waves are superimposed to the existing current, the water depth is obviously greater under the wave crest and lower under the trough. Thus, since the volume of water flowing across the section is constant with time, the velocity assumes a larger value when the cross section is smaller, i.e. during the trough passage and vice versa.

The analysis of the phase-averaged velocities has also been performed within the wave cycle at the different measurement points along the ripple profile. Figure 19 shows the phase-averaged velocity profiles at the following phases $\phi$: $\pi/4$, $\pi/2$, $3\pi/4$, $\pi$, $5\pi/4$, $3\pi/2$, $7\pi/4$ and $2\pi$. Due to the similarity of the results at the two crests, only those acquired at the onshore crest (point 5) have been reported along with the other three points (2, 3 and 4; Fig. 1). As regards the phases at which the velocity attains the maximum value, the same considerations which have been observed for Fig. 18 still apply. Figure 19 shows that during the positive wave half cycle only slight differences between the different locations can be observed. During the negative wave half cycle, when the current velocity decreases in time, the differences increase. More specifically the current velocity at point 2 decreases slightly more rapidly than at the other three points. Near the bed the lowest velocities always occur at points 4 and 5 throughout the wave cycle. This latter evidence may be related to the existence of recirculating cells. Such an existence is particularly evident at those two positions, as it can be confirmed by looking at fig. 5 of Faraci et al. (2008).
4 Conclusions

In this work the statistics of the current velocity component in the presence of a wave plus current flow propagating over a sandy bed, a gravel bed and a rippled bed have been investigated. The analysis has been performed on the basis of experimental data already acquired by the authors but never considered from this perspective. The current velocity has been split into a time-averaged velocity, an oscillating component and a turbulent fluctuation.

Firstly, the probability density function of the total near-bed velocity has been examined. It has been found that in the current only case, the probability distribution function of the near-bed velocity is very similar to the Gaussian distribution, with slight differences between sand, gravel and rippled bed. When the waves are superimposed onto the current such agreement is lost, and it has been observed that the PDF shows double peaks for which separation distance in terms of velocity is a function of the wave kinematics (i.e. relative water depth and wave steepness). To explain this process it is crucial to consider the decoupling of the current velocity into two classes, characterized by events occurring in concurrence with onshore or offshore wave velocities or upward or downward velocities, especially in the rippled bed case. Indeed, in this way, two classes of data can be clearly distinguished. The peak of the PDF of the current velocity associated with onshore directed wave velocities can be clearly distinguished. The peak of the PDF of the current velocity associated with onshore directed wave velocities has been examined. It has been found that in the current only case, the probability distribution function of the near-bed velocity is very similar to the Gaussian distribution, with slight differences between sand, gravel and rippled bed. When the waves are superimposed onto the current such agreement is lost, and it has been observed that the PDF shows double peaks for which separation distance in terms of velocity is a function of the wave kinematics (i.e. relative water depth and wave steepness). To explain this process it is crucial to consider the decoupling of the current velocity into two classes, characterized by events occurring in concurrence with onshore or offshore wave velocities or upward or downward velocities, especially in the rippled bed case. Indeed, in this way, two classes of data can be clearly distinguished. The peak of the PDF of the current velocity associated with onshore directed wave velocities always occurs at smaller velocities than that of $V_y^-$. This evidence is explained by the mass conservation principle consequent to the increasing of the cross section under the crest passage and also by a vertical advection of $x$-momentum. Along the ripple profile, however, the presence of stronger or weaker current velocities is affected by the vortex structure, generated by flow separation at the ripple crest.

The statistical analysis of the turbulent fluctuations in the wave plus current case showed that the double peaks of the PDFs disappear, since the oscillating component is not included any more. The PDF is close to a normal distribution in the sand bed case, while in the gravel and rippled bed cases although the distribution is close to be symmetric, it exhibits a flatness significantly larger than 3. Reynolds stresses are mostly negative both in the current only and in wave plus current conditions. However, in the latter case, the minimum values almost double and they are located at higher elevations. Moreover high order statistics of the turbulent velocity fluctuations generated by superimposing an orthogonal regular wave on a current have been investigated in order to understand how waves influence the current properties and the turbulence structure in the presence of different bed roughness conditions.

The aforementioned decoupling of the velocity events in terms of the positive and negative wave velocity indicates the influence of the wave phase on the current velocity. For this reason an analysis of the phase-averaged velocities has also been performed. The superposition of the waves on the currents strongly influences the velocity profiles in the current direction. The profiles exhibit a significant variability in relation to the wave phase. Indeed, they reach higher values during the second half cycle, corresponding to the passage of the wave trough, as a consequence of mass conservation and of advection of $x$-momentum in the vertical direction; the latter causes the anticipation of the phase at which the maximum of the current velocity occurs.

The results of the present work suggest that the use of a more detailed statistical characterization along with a thorough description of the phase variability of near-bed velocity could certainly contribute to a better modelling of coastal sediment transport and related processes.

**Notation**

$D$ = water depth  
$D_{50}$ = median grain size  
$F$ = flatness  
$H$ = wave height  
$N$ = relative number of occurrences  
$N^*$ = number of occurrences in each class of $V_x$  
$n$ = number of classes of $V_x$  
$S$ = skewness  
$T$ = wave period  
$V_{DM}$ = depth averaged velocity in the direction of the current  
$V_x$ = velocity component in the direction of the current  
$V_y$ = velocity component in the direction of the waves  
$V_z$ = velocity component in the vertical direction  
$\langle V_x \rangle$ = ensemble averaged velocity in the direction of the current  
$V_x^+$ = velocity in the direction of the current corresponding to positive $V_x$  
$V_x^-$ = velocity in the direction of the current corresponding to negative $V_x$  
$V_y^+$ = velocity in the direction of the current corresponding to positive $V_y$  
$V_y^-$ = velocity in the direction of the current corresponding to negative $V_y$  
$\overline{V}_x$ = time averaged velocity in the direction of the current  
$V'_x$ = turbulent fluctuating velocity in the direction of the current  
$\ddot{v}_x$ = oscillating velocity in the direction of the current  
$x$ = direction of the current  
y = direction of the waves  
z = vertical direction positive upward  
$\Delta V'_x$ = distance between two peaks of a PDF  
$\theta$ = angle of mean flow  
$\sigma$ = standard deviation  
$\phi$ = wave phase
Funding
This work has been funded by Italian Ministry of University, Education and Research, PRIN 2012 Project “Hydro-morphodynamics modelling of coastal processes for engineering purposes”, and by the EC project Hydralab+ [contract no. 654110].

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References
Andersen, K. H., & Faraci, C. (2003). The wave plus current flow over vortex ripples at an arbitrary angle. Coastal Engineering, 47, 431–441. doi:10.1016/S0378-3839(02)00158-8
Arnskov, M. M., Fredsøe, J., & Sumer, B. M. (1993). Bed shear stress measurements over a smooth bed in three-dimensional wave-current motion. Coastal Engineering, 20, 277–316.
Cheng, N. S. (2006). Influence of shear stress fluctuation on bed particle instability. Physics of Fluids, 18(9), 096602.
Faraci, C., Foti, E., Marini, A., & Scandura, P. (2012). Waves plus currents crossing at a right angle: Sandpit case. Journal of Waterway, Port, Coastal, and Ocean Engineering, 138(5), 339–361. doi:10.1061/(ASCE)WW.1943-5460.0000140
Faraci, C., Foti, E., & Musumeci, R. E. (2008). Waves plus currents crossing at a right angle: The rippled bed case. Journal of Geophysical Research, 113(C07018), 1–26. doi:10.1029/2007JC004468
Fernando, P. C., Guo, J., & Lin, P. (2011). Wave-current interaction at an angle 1: Experiment. Journal of Hydraulic Research, 49(4), 424–436.
Fredsøe, J., Andersen, K. H., & Sumer, B. M. (1999). Wave plus current over a ripple-covered bed. Coastal Engineering, 38, 177–221.
Friedrich, H., Nikora, V., Melville, B. W., & Coleman, S. E. (2006, September 10–13). Statistical interpretation of geometric differences in ripple and dune shapes. In 7th international conference on hydroscience and engineering, Philadelphia. IAHR.
Grant, W. D., & Madsen, O. S. (1979). Combined wave and current interaction with a rough bottom. Journal of Geophysical Research, 84(C4), 1797–1808.
Grass, A. J., & Ayoub, R. N. M. (1983, November 14–19). Bed load transport of fine sand by laminar and turbulent flow. In 18th international conference on coastal engineering, Cape Town, South Africa (pp. 1589–1599). ASCE.
Huang, Z., & Mei, C. C. (2003). Effects of surface waves on a turbulent current over a smooth or rough seabed. Journal of Fluid Mechanics, 497, 253–287.
Kim, J., Moin, P., & Moser, R. (1987). Turbulence statistics in fully developed channel flow at low reynolds number. Journal of Fluid Mechanics, 177, 133–166.
Lim, K. Y., & Madsen, O. S. (2016). An experimental study on near-orthogonal wave-current interaction over smooth and uniform fixed roughness beds. Coastal Engineering, 116, 258–274.
Lim, K. Y., Madsen, O. S., & Cheong, H. F. (2012, July 1). Current characteristics in the presence of near orthogonal waves. In 33rd international conference on coastal engineering, Santander, Spain. ASCE.
Lodahl, C. R., Fredsøe, J., & Sumer, B. M. (1998). Turbulent combined oscillatory flow and current in a pipe. Journal of Fluid Mechanics, 373, 313–348.
Madsen, O. S., Negara, A. S., Lim, K. Y., & Cheong, H. F. (2010, 30 June–5 July). Near-bottom flow characteristics of currents at arbitrary angle to 2d ripples. In 32nd international conference on coastal engineering, Shanghai, China. ASCE.
Mathiesen, P. P., & Madsen, O. S. (1996). Waves and currents over a fixed rippled bed. 2. Bottom and apparent roughness experienced by currents in the presence of waves. Journal of Geophysical Research, 101(C7), 16543–16550.
Musumeci, R. E., Cavallaro, L., Foti, E., Scandura, P., & Blondaux, P. (2006). Waves plus currents crossing at a right angle: Experimental investigation. Journal of Geophysical Research, 111(C7). doi:10.1029/2005JC002933
Nikora, V. I., Goring, D. G., & Biggs, B. J. F. (1998). On gravel bed roughness characterization. Water Resources Research, 34(3), 517–527.
Parker, G., Paola, C., & Leclair, S. (2000). Probabilistic exner sediment continuity equation for mixtures with no active layer. Journal of Hydraulic Engineering, 126(11), 818–826.
Ransomas, K. I. M., & Sleath, J. F. A. (1994). Combined oscillatory and steady flow over ripples. Journal of Waterway, Port, Coastal and Ocean Engineering, 120(4), 331–346.
Scandura, P., Faraci, C., & Foti, E. (2016). A numerical investigation of acceleration-skewed oscillatory flows. Journal of Fluid Mechanics, 808, 576–613.
Simons, R. R., Grass, T. J., & Mansour-Tehrani, M. (1992, October 4–9). Bottom shear stresses in the boundary layer under waves and currents crossing at right angle. In 23rd international conference on coastal engineering, Venice, Italy (Vol. 1, pp. 604–617). ASCE.
Simons, R. R., Grass, T. J., Saleh, W. M., & Mansour-Tehrani, M. (1994, October 23–28). Bottom shear stresses under random waves with a current superimposed. In 24th international conference on coastal engineering, Kobe, Japan. ASCE.
Willert, C. E. (2015). High-speed particle image velocimetry for the efficient measurement of turbulence statistics. Experiments in Fluids, 56,17.
Yuan, J., & Madsen, O. S. (2015). Experimental and theoretical study of wave-current turbulent boundary layers. Journal of Fluid Mechanics, 765, 480–523.