Experimental Investigation of Coherent Structures in Wave Boundary Layers - DTU Orbit  
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Synchronized flow visualization experiments, wall shear stress and LDA measurement of the combined oscillatory flow and current boundary layer were made in the same oscillating water tunnel as the one used in the work by Jensen et al. (1989) and Lodahl et al. (1998). The range of wave Reynolds-number $\text{Re}_w = aU_m/\nu$, was from practically 0 to $5.0 \times 10^5$; in which $\nu$ is the kinematic viscosity, $a$ is the amplitude of the free-stream particle motion and $U_m$ is the amplitude of the free-stream velocity. For the current Reynolds-number $\text{Re}_c = 4R_hV/\nu$, the range was from 0 (oscillatory flow alone) to $2.7 \times 10^4$; in which $R_h$ is the hydraulic radius and $V$ is the mean velocity of the current.

For the case of oscillatory flow alone, three kinds of coherent structures have been identified over certain wave Reynolds-number intervals: (1) Small-scale longitudinal streaks ($30.000 < \text{Re}_w < 150.000$), (2) Transverse vortex tubes ($75.000 < \text{Re}_w < 300.000$) and (3) Turbulent spots ($150.000 < \text{Re}_w < 500.000$). In addition to the Reynolds-number dependency, these structures occur only over certain phase intervals.

The transverse vortex tubes are caused due to the inflection point shear-layer instability mechanism. These structures were reported in the literature before by researchers such as Sarpkaya (1993), Foster et al. (1994) and Das and Arakeri (1998). Of particular interest are the turbulent spots. To the author’s knowledge, although extensively studied in steady boundary layers, these coherent structures have not been reported for oscillatory boundary layers before (It may be mentioned that turbulent spots may be viewed as building blocks of the fully developed turbulent boundary layers).

The present measurements reveal that spikes in the wall shear stress experienced during deceleration (reported in the previous research, e.g. Hino et al. (1983) and Jensen et al. (1989)) are caused by turbulent spots. The magnitude of these spikes can be as much as a factor of 3 to 4 larger (sometimes even larger) than the maximum value caused by the maximum free stream flow velocity and therefore these structures have significant implications for sediment transport processes.

In the wave-dominated combined oscillatory flow and current ($V/U_m < 0.33$), the coherent structures are essential identical to the case of oscillatory flow alone. That is, the transition to turbulence occurs in both half-cycles of the combined oscillatory flow and current through the formation of turbulent spots. However, since the current acts as an extra adverse pressure gradient for the second half-cycle the combined flow, turbulent spots form as early as $\text{Re}_w = 1 \times 10^5$ in this half-cycle. This value is $1.5 \times 10^5$ for the oscillatory flow alone case. Likewise, the current acts as an extra favorable pressure gradient in the first half-cycle of the combined flow, whereby transition to turbulence is delayed here.

For $V/U_m > 0.33$ transition to turbulence also occurs through the formation of turbulent spots; however, only in the first half-cycle. The analysis of the flow visualizations revealed that this transition may be regarded as the restoration of the turbulent steady current boundary layer (i.e. current-dominated transition to turbulence). The restoration of the turbulent steady current boundary layer, starts in the later part of first half-cycle, and as $\text{Re}_c$ increases, the transition shifts to smaller values of $\omega t$. Furthermore, the transition (or the formation of turbulent spots) in the first half-cycle occur for this situation at $\text{Re}_w < 1.5 \times 10^5$.

Furthermore, an exploratory study of the rough-wall oscillatory boundary layer flow has shown that the transverse vortex tubes and turbulent spots are present irrespective of wall roughness conditions.

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