LAMINAR-TO-TURBULENT TRANSITION IN OSCILLATORY WAVE BOUNDARY LAYERS

Selman Baysal, Çanakkale Onsekiz Mart University; and also Istanbul Technical University, selmanbaysal@comu.edu.tr
V. S. Ozgur Kirca, BM SUMER Consultancy & Research; and also Istanbul Technical University, kircave@itu.edu.tr
B. Mutlu Sumer, BM SUMER Consultancy & Research, bms@bmsumer.com

INTRODUCTION

The orbital motion of water particles under a progressive wave in shallow waters becomes a straight line parallel to the bottom, i.e., oscillatory motion, at the seabed. A new time-dependent boundary layer develops over the seabed for each half-cycle of this motion. The turbulent oscillatory wave boundary layer is of great importance in many engineering applications, especially in coastal engineering. Even though both laminar and turbulent regimes have been considered in oscillatory boundary layers, of particular interest is the transitional regime. The laminar-to-turbulent transition first occurs in the form of tiny turbulent patches close to the wall, called turbulent spots, just before the near-bed flow reversal. These coherent structures are arrowhead-shaped isolated areas where the flow bursts with intense oscillations, in an otherwise laminar boundary-layer flow (Sumer and Fuhrman, 2020). Single or multiple spikes in the bed shear stress signal reaching up to 3 or 4 times the magnitude of the bed shear stress is a good indicator of a turbulent spot (Carstensen et al., 2010). Although much experimental and numerical research has been conducted (e.g., Carstensen et al., 2010; Jensen et al., 1989), there are still many unanswered questions regarding the transition. This study aims to address these questions using the DNS method, which has become very popular in turbulence-related problems (e.g., Mazzuoli et al., 2011; Xiong et al., 2020), by focusing on observing turbulent spots and locating their birthplace, concurrently with the bed shear stress under the spot structure. The present study is being conducted in close collaboration with Professor Liang Cheng and Drs. Chengwang Xiong and Chengjiao Ren of the University of Western Australia. The study is only in the early stages, and some early results will be presented at the meeting.

COMPUTATIONAL METHODS

The DNS model was conducted by the open-source Nektar++ framework. This section summarizes the implemented method originally developed by Xiong et al. (2020). The governing equations for the oscillatory flow were solved using the *IncNavierStokesSolver* embedded in Nektar++. A 2-D mesh was defined, and Fourier discretization was implemented in the spanwise direction to resolve the full 3-D features of the flow. An isolated roughness element was placed on the center of the wall by using *LinearElasticSolver* to trigger the initial perturbations. This hump was removed at the very moment the primary vortex tube appeared to ensure that the development of the observed coherent structure was not affected by this temporal roughness element. The length, height, and breadth of the computational domain were chosen to be 45000, 3500, and 900, respectively, in terms of the wall units, namely $x_i^+ = x_i U_{fm}/\nu$ with U_{fm} being the amplitude of the friction velocity and ν is the kinematic viscosity. While the no-slip condition was introduced on the lower boundary (bed), the slip boundary condition was applied to the upper boundary of the computational domain. A high-order Neumann pressure condition ($\partial p/\partial x = 0$) was adopted to both the lower and upper boundaries, and a periodic condition was specified for the spanwise and streamwise boundaries. Also, the time-step (Δt) was carefully selected concerning the Courant-Friedrichs-Lewy (stability) criterion. The present model was validated against the results of Xiong et al. (2020).

RESULTS AND CONCLUSIONS

The bed shear stress signal (τ_0), considered a reliable indicator of the turbulence, was investigated after a full period following the removal of the hump to ensure that the conditions initiating the laminar-to-turbulent transition were independent of the previous period. The early results of the study reveal that the coherent structures can be explicitly identified by the present method, whereby these structures can be traced.

Fig. 1 shows the contour plots of non-dimensional bed shear stress, i.e., $|\tau_0|/\tau_{0m}$ with τ_{0m} being the amplitude of the bed shear stress during the wave period. The Reynolds number in the figure caption is $Re = U_{0m}\, a/\nu$, in which U_{0m} is the amplitude of the free-stream velocity U_0 and a is the amplitude of oscillatory motion. The "probe" locations, indicated by P1, P2, and P3, were placed considering the trajectory of the turbulent spots. The distances were given in terms of the wall units, x_i^+. In Fig. 1, ωt is the phase described by $U_0 = U_{0m} \sin \omega t$, where $\omega = 2\pi/T$ is the angular frequency of the oscillating flow.

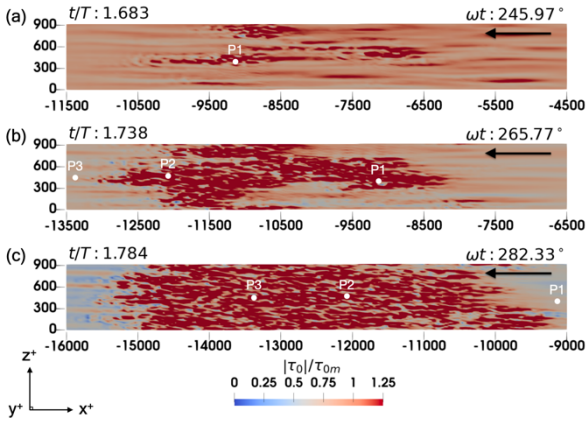


Figure 1 - The bed shear stress contour plots of developing turbulent spots during the third half-cycle of the flow after the temporary hump is removed: (a) early stage of the turbulent spots; (b) and (c) the turbulent spots grow in size and shape. *Re* = 1.8×10^5. Free-stream flow direction from right-to-left as marked in the figure.

While Fig. 1(a) shows the early stage of turbulent spots (i.e., twisting and turning motion induced by the longitudinal streaks), an arrowhead-shaped turbulent spot detected at the phase value of about $\omega t = 265°$ (i.e., 85° after the flow reversal) and resulting "fully"-developed turbulent boundary layer flow can be seen in Figs. 1(b) and (c), respectively.

In Fig. 2, the time series of bed shear stress obtained from the probes indicated in Fig. 1 is presented. As seen in Fig. 2(a), the magnitude of spikes in the bed shear stress signal generated by the turbulent spots reaches to a value almost 3 times (4-5 times in Fig. (b) and (c)) larger than the maximum bed shear stress (τ_{0m}). It was also seen that the flow reversal delays due to turbulence, i.e., the phase lead ϕ decreases with the transition, which agrees well with the experimental observations of Carstensen et al. (2010).

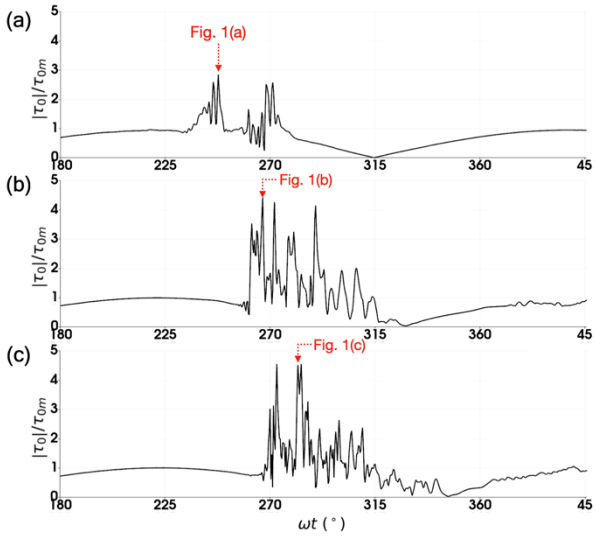


Figure 2 - The time series of bed shear stress that corresponds to the passage of the flow structures over the probe locations illustrated in Fig. 1 ($Re = 1.8\times10^5$). The arrows refer to the time instant presented in the previous figure, respectively.

The focus in the remainder of the study will be directed towards the investigation of the origin of the turbulence spots, to shed light on the transition to turbulence in oscillatory boundary layers.

ACKNOWLEDGEMENT

This work is funded by the Scientific and Technological Research Council of Turkiye (TUBITAK) through the project titled "Qualitative and Quantitative Investigation of Laminar-to-Turbulent Transition in Steady and Unsteady Boundary Layers" under Grant No. 122M024.

REFERENCES

Carstensen, Sumer, and Fredsøe (2010): Coherent structures in wave boundary layers. part 1. oscillatory motion, Journal of Fluid Mech., vol. 646, pp. 169-206.

Jensen, Sumer, and Fredsøe (1989): Turbulent oscillatory boundary layers at high Reynolds numbers, J. Fluid Mech., vol. 206, pp. 265-297.

Mazzuoli, Vittori, and Blondeaux (2011): Turbulent spots in oscillatory boundary layers, Journal of Fluid Mech., vol. 685, pp. 365-376.

Sumer and Fuhrman (2020): Turbulence in Coastal and Civil Engineering, World Scientific.

Xiong, Qi, Gao, Xu, Ren, and Cheng (2020): The bypass transition mechanism of the stokes boundary layer in the intermittently turbulent regime, Journal of Fluid Mech., vol. 896, A4.