TURBULENCE-RESOLVING MODELING OF OSCILLATORY BOUNDARY LAYER FLOWS

Allocation: Illinois/993.725 Knh
PI: Marcelo García[1]
Co-PI: Paul Fischer[1]
Collaborators: Dimitrios K. Fytanidis[1], Jose M. Mier[1]

[1]University of Illinois at Urbana–Champaign

EXECUTIVE SUMMARY

Oscillatory boundary layer flows play an important role in coastal engineering, offshore engineering, and coastal sediment transport. However, current state-of-the-art models fail to accurately predict the complex interaction of turbulent oscillatory flow with sediment transport, highlighting the existing knowledge gaps regarding the complex interactions among the oceanic flow, the coastal bottom, and sedimentation processes. Recent experimental and numerical studies conducted by the research team indicate the presence of a phase-lag between the time instance when the maximum bed shear stress occurs with respect to the maximum free-stream velocity in transitional oscillatory boundary layer flows. However, the effect of turbulent coherent structures and turbulence modulation under severe acceleration remain unknown. The current work is the first computational effort to simulate the effect of flow coherent structures and turbulent events such as sweeps and ejections on the maximum bed shear stress phase difference compared to the maximum free-stream velocity value.

RESEARCH CHALLENGE

Recent experimental studies conducted in the Large Oscillatory Water-Sediment Tunnel at the Ven Te Chow Hydrosystems Laboratory at the University of Illinois at Urbana–Champaign examine the transition between the laminar and turbulent flow regimes with a smooth bed. The results indicate a significant change in the widely used phase difference diagram between the maximum bed shear stress and the maximum free-stream velocity [1]. This observation is extremely important for the field of environmental fluid mechanics and coastal sediment transport. Nevertheless, due to the limitation of the applied pointwise experimental technique (Laser Doppler Velocimetry), it was not possible to explicitly associate this finding with the development of three-dimensional flow turbulence structures usually referred to as turbulence coherent structures.

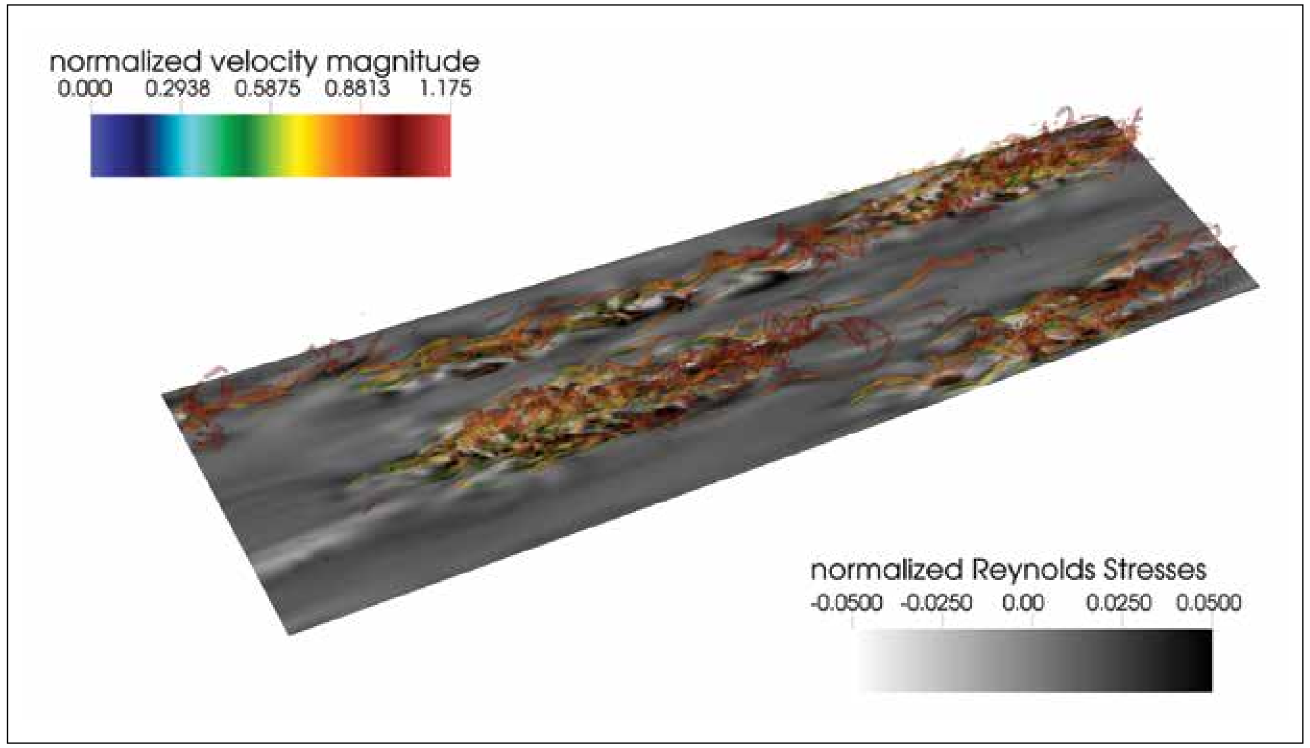

Figure 1: Turbulent spot visualization under oscillatory flow conditions.

This work is the first computational effort to quantify the effect of the three-dimensional turbulent flow structures on the phase difference between the maximum bed shear stress and the maximum free-stream velocity. Also, it will be the first numerical study that will quantify the effects of flow regime and bed characteristics on the turbulent characteristics and quadrant analysis under oscillatory flow conditions. It will also be among the first studies that will study the momentum exchange between the free-stream oscillatory flow and the seabed unsteady flow conditions.

METHODS & CODES

In this work, the research team developed a direct numerical simulation (DNS) model capable of simulating the complex oscillatory boundary layer flow using the spectral element method framework provided by the highly scalable open-source code Nek5000 [2]. Except for the analysis of turbulence characteristics of oscillatory boundary layer flow over different flow conditions, the present work requires use of a proper model for the simulation of the suspended sediment using an Eulerian approach and proper boundary conditions for the sediment mass exchange between the coastal bed and the free-stream flow (*e.g.*, [3-4]).

Due to the data-rich outputs of our simulations, the team is collaborating with the Data Analytics and Visualization (DAV) group of the National Center for Supercomputing Applications in an effort to find an efficient way to visualize the coherent flow structures and the numerical results. The team plans to apply high-performance, data-intensive visualization and analysis techniques by means of producing high-quality, interactive visualizations of simulation results in an effort to uncover new knowledge through the efficient analysis of the information-rich data. Special attention will be given to the application of efficient methods for the estimation of the geometric characteristics of coherent flow structures as well as the quantification of their effect on flow behavior.

RESULTS & IMPACT

DNS results for mean flow and turbulent statistics were compared against previous experimental and numerical observations [1,5] and the comparison agrees well both qualitatively and quantitatively. Quadrant analysis shows that turbulent events such as sweeps and ejections dominate for most of the period. Phase difference results agree well with the previous experimental findings.

This work is the first in the literature that explores the effect of turbulence characteristics of the flow—and particularly the turbulent flow structures, such as turbulent spots (Fig. 1)—on the phase difference between maximum bed shear stress and free-stream velocity. The team identified hairpin vortices for the first time in the oscillatory boundary layer in addition to other flow structures previously reported in the literature (vortex tubes and turbulent spots). They studied the effect of these structures on the turbulence statistics and found that vortex tubes seem to have minimal effect. On the contrary, turbulent spots, which are spatially and temporarily sporadic, lambda-shaped, highly energetic structures, have a significant effect on turbulence characteristics.

WHY BLUE WATERS

The present work pushes the limit of the turbulent-resolving flow modeling of oscillatory flows. The dimensions of the computational domain were chosen based on the prior knowledge of experimental observation of turbulent spots [6,7] to ensure that the computational domain is big enough to allow these turbulent structures to develop. This size is larger than any of the previous domains reported in the literature, and together with the increased number of computational points (on the order of 0.8 billion) make this study the first of its kind in terms of the computational resources and the high-performance computing facilities it requires. Thus, it can be materialized only on a petascale supercomputer such as Blue Waters.