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OFF-WALL BOUNDARY CONDITIONS FOR BOUNDED TURBULENT FLOW SIMULATIONS

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Abstract We investigated the possibility of modeling off-wall boundary conditions for bounded turbulent flows. Such boundary conditions circumvent the need to resolve the buffer layer near the wall by providing conditions directly above it for the overlying flow. Our objective is to model the effect of the buffer layer on the overlying flow as an off-wall, Dirichlet boundary condition for the flow variables. We selected the plane at $y^+ \approx 100$ as our off-wall boundary, since this plane can be interpreted as a notional interface between the buffer and logarithmic regions. We tested different boundary conditions on channel flow with increasing levels of abstraction/modeling, starting from exact, time-resolved conditions from a previous DNS, all the way to a reduced-order model obtained from minimal flow units of a transitional boundary layer.

MOTIVATION

The direct simulation of turbulent flows at moderate to high Reynolds numbers is inaccessible for any existing computing facility. However, LES can successfully reproduce such flows of practical engineering importance, but it requires that a sufficiently large separation of scales exists between those at which energy is generated and those at which it is dissipated. Unfortunately, that does not hold near walls, since the inertial scale approaches the viscous scale linearly as the distance to the wall decreases. This forces the resolution requirements of LESs to approach those of DNSs near walls, losing the advantage of LES, or modeling is required in the near-wall layer. To overcome this difficulty, we propose a novel set of boundary conditions for the outer flow away from the wall.

Pascarelli *et al.* [1] developed the idea of simulating the overlying flow separately from the buffer layer by using what they called a multi-block LES. The outer flow was computed with a lower resolution grid while the wall layer was represented by two blocks with a higher resolution grid but with half the width of the outer layer. This idea can be extended by removing the buffer layer completely and modeling its effect on the rest of the flow as a boundary condition, imposed where the top of the buffer layer would be. Podvin and Fraigneau [2] generated synthetic boundary conditions of this sort from proper-orthogonal-decomposition eigenfunctions, which need to be obtained a priori. Assuming that the turbulent fluctuations are self-similar across the log layer, Mizuno and Jiménez [3] constructed dynamic boundary conditions from information in the overlying flow. Park *et al.* [4] provided strong evidence that there is little difference between the structure and transport processes of a developed turbulent boundary layer and of turbulent spots that appear in transition by comparing statistics based on both the velocity vector and the velocity gradient tensor for the two cases.

These prior studies motivated us to develop and test an off-wall boundary condition built from transitional wall layer flow. The effect of the buffer layer is modeled as a pattern of periodic blocks similar to the minimal unit of Jiménez and Moin [5]. The blocks are constructed from a transitional boundary layer DNS of Sayadi *et al.* [6], with sizes selected so that they are statistically and spectrally representative of fully turbulent flow and so that they contain the dominant structures at $y^+ \approx 100$, as educed from direct mode decomposition. The model is reduced to the imprint of such blocks on this plane, and it has the form of a collection of Fourier modes in space and time that comprise $\sim 1\%$ of the parameters necessary to describe the full flow field there, while it reproduces $\sim 90\%$ of the amplitudes of the flow statistics. Visual comparison with the original signal shows that the reconstruction is a reasonable representation in which the dominant, energy-carrying structures are present, although some minor or short-lived features are missing.

IMPLEMENTATION

To test our off-wall boundary conditions we chose to simulate a turbulent channel at $\mathrm{Re}_\tau = 395$ with DNS resolution. This is a particularly simple case because the boundary condition can be imposed in a uniform lattice, unlike the boundary layer where the effect of streamwise evolution must be taken into account. Additionally, the large-scale modulation of the near wall flow, which would need to be addressed at larger Reynolds numbers, is very weak.

We adapted the incompressible, fractional-step channel code of Bose *et al.* [7] to allow for non-zero, off-wall boundary conditions. Finite difference discretization in space, with grid stretching in the wall-normal direction and a Runge-Kutta/Crank-Nicholson scheme in time, was implemented. The doubly-periodic domain size was chosen so that an exact number of boundary-condition blocks can be imposed at the virtual boundary plane in the lattice. We conducted a set of simulations in which the different levels of abstraction in our model were introduced progressively. First, a full DNS of the whole channel was carried out, and the time histories of the flow velocities at the designated $y^+ \approx 100$ planes

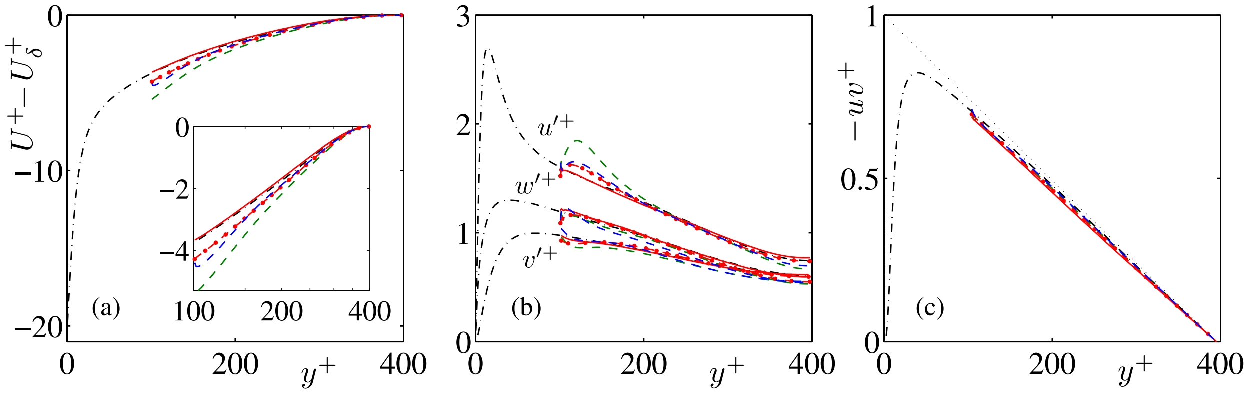

Figure 1. Flow statistics from the present channel flow simulations at $\mathrm{Re}_\tau \approx 395$. (a) mean velocity profile; (b) rms velocity fluctuations; (c) Reynolds shear stress. − · −, full-channel DNS; ——, off-wall exact boundary conditions; • • • • •, reduced-order modeled boundary conditions obtained from the exact ones; − − − −, from 'minimal' channels; − − − −, from a 'minimal' unit block at $\mathrm{Re}_\theta \approx 500$ in a transitional boundary layer [6]; − − − −, from a 'minimal' unit block at $\mathrm{Re}_\theta \approx 1300$ from [6].

were saved. In a second simulation, starting from the same initial condition, those time histories were implemented as 'exact' off-wall boundary conditions. In a third simulation, the same set of time histories were used to synthesize reduced order boundary conditions by Fourier transformation, followed by truncation. To test the concept of a repeated lattice as a boundary condition, a similar, reduced set was obtained from a 'minimal' channel, of roughly one third the length and width of the benchmark case, on which the resulting conditions were imposed. Finally, the reduced-order conditions obtained from minimal unit blocks in a transitional boundary layer [6] were tested.

RESULTS

Preliminary results are portrayed in Figure 1, which shows velocity statistics, including the mean velocity profiles, the rms velocity fluctuations and the Reynolds shear stress, for our set of simulations. The results with off-wall boundary conditions are in very good agreement with those of the full channel, except in a thin layer near the off-wall boundary plane, which develops extraneous kinks in the rms velocity distributions. Those kinks are present even for 'exact' boundary conditions, for which they grow in intensity with time, although the time span considered for the statistics in that case was too short for the kinks to be noticeable in the figure. Similar kinks appear in simulations with off-wall boundaries by other authors [2, 3], who argued that their appearance is due to the decoupling of the boundary condition and the overlying flow, so that the flow requires an adjustment region to adapt to the prescribed boundary values. In our simulations, the intensity of the kinks seems to increase as more layers of abstraction are added to the boundary condition. Nevertheless, the agreement with full-channel results is remarkable, particularly in the case of boundary conditions from transitional boundary layer data, considering they are obtained from an entirely different flow. The most noticeable difference is the mismatch in the mean velocity profile. This mismatch is due to the very small relative differences in the Reynolds stress. Since the Reynolds and viscous stresses must sum up to the same, linear-with-y, total stress, and the viscous stress is much smaller than the Reynolds stress in the channel core, the small relative error in the latter translates into a larger relative error in the former. This larger error in viscous stress is in fact a larger error in the slope of the mean velocity profile. Nevertheless, even if the mismatch in the profile is substantially larger for the boundary condition derived from boundary-layer data, it is still of order $\Delta U^+ \approx 1$ at most, which is $\sim 5\%$ of the centerline velocity.

References

[1] A. Pascarelli, U. Piomelli, and G. Candler. Multi-block large-eddy simulations of turbulent boundary layers. *J. Comp. Phys.*, **157**:256–279, 2000.

[2] B. Podvin and Y. Fraigneau. Synthetic wall boundary conditions for the direct numerical simulation of wall-bounded turbulence. *J. Turbulence*, **12**:1–26, 2011.

[3] Y. Mizuno and J. Jiménez. Wall turbulence without walls. Submitted to *J. Fluid Mech.*, 2012.

[4] G. Park, J. Wallace, X. Wu, and P. Moin. Boundary layer turbulence in transitional and developed states. *Phys. Fluids*, **24**:035105, 2012.

[5] J. Jiménez and P. Moin. The minimal flow unit in near-wall turbulence. *J. Fluid Mech.*, **225**:213–240, 1991.

[6] T. Sayadi, C. Hamman, and P. Moin. Direct numerical simulation of complete H-type and K-type transitions to turbulence. Submitted to *J. Fluid Mech.*, 2012.

[7] S. T. Bose, P. Moin, and D. You. Grid-independent large-eddy simulation using explicit filtering. *Phys. Fluids*, **22**:105103, 2010.