INTERNATIONAL JOURNAL FOR NUMERICAL METHODS IN FLUIDS
Int. J. Numer. Meth. Fluids 2009; **60**:227–235
Published online 13 August 2008 in Wiley InterScience (www.interscience.wiley.com). DOI: 10.1002/fld.1884

SHORT COMMUNICATION

Inflow conditions for inhomogeneous turbulent flows

Mustafa Barri[1,*,†], George K. El Khoury[2], Helge I. Andersson[1] and Bjørnar Pettersen[2]

[1]*Department of Energy and Process Engineering, The Norwegian University of Science and Technology, NO-7491 Trondheim, Norway*
[2]*Department of Marine Technology, The Norwegian University of Science and Technology, NO-7491 Trondheim, Norway*

SUMMARY

A cost-effective method to generate inflow conditions for direct numerical simulations of wall-bounded flows is presented. The method recycles a finite-length time series of instantaneous velocity planes extracted from a precursor simulation and has earlier proved efficient for free shear layers. Now a spatially developing plane channel flow is considered. Different durations t_s of the time series are tested and compared. Excellent agreement with fully developed channel flow statistics is observed when t_s equals or exceeds the large-eddy turnover time scale. The present results are more realistic than those obtained with synthetic turbulence generation and at the same time substantially cheaper than running an auxiliary simulation in parallel. Copyright © 2008 John Wiley & Sons, Ltd.

Received 4 March 2008; Revised 15 June 2008; Accepted 16 June 2008

KEY WORDS: wall-bounded flow; turbulence; inhomogeneous flow; DNS; inflow BC; CFD

1. INTRODUCTION

Specification of realistic inflow boundary conditions for spatially developing turbulent flows is still a problematic task since the use of periodic boundary conditions is not suitable. Since DNS solves for all scales in time and three-dimensional space the inflow conditions should contain wide ranges of time and length scales which represent correctly the turbulent behavior based on the continuity

*Correspondence to: Mustafa Barri, Department of Energy and Process Engineering, The Norwegian University of Science and Technology, NO-7491 Trondheim, Norway.
†E-mail: barri@ntnu.no

Contract/grant sponsor: The Research Council of Norway

condition and furthermore the momentum balance. Several methods of different complexity have been investigated previously in order to provide inflow data for inhomogeneous turbulent flows.

Kristoffersen and Andersson [1] used the simplest method to generate inflow boundary conditions by adding perturbations on a laminar solution from which the turbulence then develops. This method may require a very long streamwise computational domain to allow realistic turbulence to develop from the imposed perturbations. Spalart and Watmuff [2] introduced the '*fringe method*' in order to simulate the self-similar turbulent boundary layer using periodic boundary conditions by adding a forcing term to the Navier–Stokes equations close to the inflow and outflow. The fringe method decreases the boundary layer thickness and re-modifies an equilibrium boundary layer before it is introduced again as inflow. Lund *et al.* [3] used a rescaling technique for the velocity field at a certain location downstream of the computational domain and re-used it as inflow condition in order to simulate the self-similar turbulent boundary layer. For spatially developing channel flow Johansson and Andersson [4] used proper orthogonal decomposition (POD) by solving evolution equations only for the most energetic eddies in the flow to generate dynamic flow boundary conditions. Later Keating *et al.* [5] compared several methods to generate turbulent inflow: a synthetic method, a recycling method and a forcing method using large-eddy simulations (LES).

'*Time-dependent*' inflow is the most realistic type of inflow conditions for spatially developing turbulent flows where the inflow boundary conditions are obtained from a separate auxiliary (precursor) simulation with periodicity in the streamwise direction. The auxiliary case must be run either synchronously or prior to the actual computation for spatially developing turbulent flow. A finite time series of data taken from the auxiliary case is either to be stored on disk and re-used as inflow or to be read simultaneously as an inflow for the actual simulation. Using this approach several spatially developing flows have been simulated [6–8]. However, this method is computationally very expensive in terms of CPU time and storage costs since the auxiliary case must be simulated for long time in order to give long enough time series which is essential to get reasonable statistics for the spatially developing flow.

Li *et al.* [9] simulated a spatially developing mixing layer. As inflow condition they used a finite time series of instantaneous velocity planes with duration equal to the integral time scale of the flow taken from a periodic simulation. This signal was transformed into a periodic one by using a conventional windowing technique and was re-used in the actual simulation by recycling through these input velocity planes as many times as required to obtain converged statistics. Li *et al.* [9] demonstrated that their method appeared as a cost-effective strategy in the generation of inflow data for turbulent free shear layers as compared to using time-dependent inflow. The success of their method was ascribed to the inviscid instability mechanism due to the presence of an inflection point in the mean velocity profile. This instability constitutes a powerful mechanism for the amplification of small disturbances and therefore tends to destabilize the flow and rapidly weaken the periodicity induced by the inflow. It was left as an unanswered question whether or not this method also can be applied to wall-bounded flows. The aim of the present study is to address this yet open issue.

2. NUMERICAL CONFIGURATIONS

Direct numerical simulations of spatially developing turbulent channel flow have been performed by solving the incompressible Navier–Stokes equations using a finite volume code (MGLET) on

DOI: 10.1002/fld

staggered grid. The code is second-order accurate both in time and space [10]. Several channel flow cases have been simulated in order to investigate the effect of the inflow boundary conditions on the turbulent flow at Reynolds number $Re_\tau \equiv u_\tau h/v$ of 180, where h is half of the channel height. The computational box size is $(L_x \times L_y \times L_z) = (4\pi h \times 2h \times 2\pi h)$ and the grid resolution is $(N_x \times N_y \times N_z) = (192 \times 192 \times 192)$ in streamwise, wall-normal and spanwise directions, respectively. No-slip conditions were imposed at the solid walls and periodic boundary conditions were used in the homogeneous spanwise direction. All the cases have been sampled for $8.4h/u_\tau$ with time step $0.0003h/u_\tau$ using the same computational box size, Reynolds number and spatial/temporal resolution.

The auxiliary simulation (*Case* 1) has been performed using periodic boundary conditions also in the streamwise direction. The spatially developing cases (*Case* 2 till *Case* 6) have been simulated by applying inflow–outflow conditions in the streamwise direction. The inflow condition is based

Table I. Simulation cases. The total simulation time is $16.8h/u_\tau$.

	t_s	Flow type
Case 1	Periodic	Auxiliary-fully developed
Case 2	$0.03h/u_\tau$	Spatially developing
Case 3	$0.3h/u_\tau$	Spatially developing
Case 4	$1.0h/u_\tau$	Spatially developing
Case 5	$2.0h/u_\tau$	Spatially developing
Case 6	$16.8h/u_\tau$	Time dependent-spatially developing

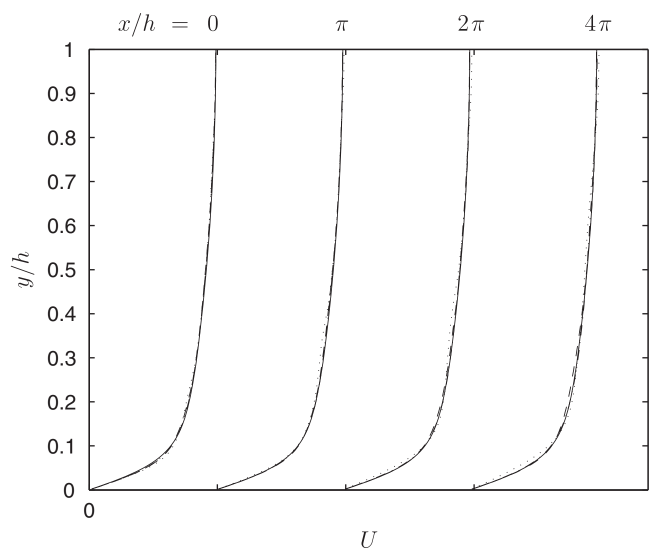

Figure 1. The mean velocity profiles at different cross-sections. —, *Case* 1; ···, *Case* 2; – – –, *Case* 3; – · –, *Case* 4.

DOI: 10.1002/fld

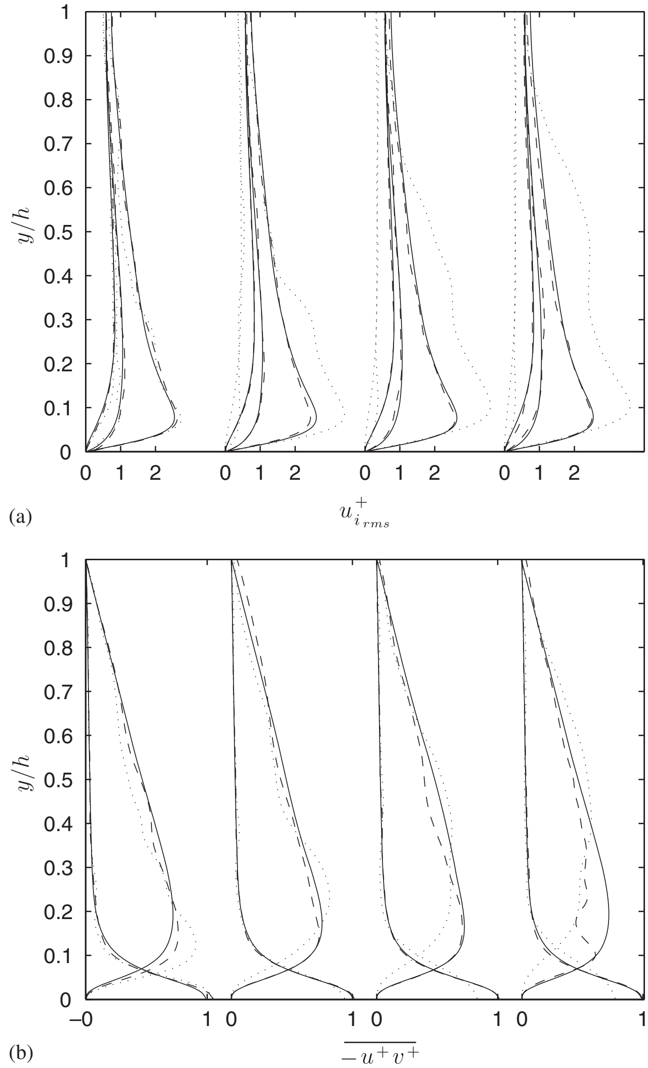

Figure 2. Turbulent statistics at the same cross-sections as in Figure 1: (a) turbulent intensities and (b) Reynolds and viscous shear stress. —, *Case* 1; $\cdots$, *Case* 2; – – –, *Case* 3.

on different finite-length time signals of the instantaneous velocity planes extracted at a certain cross-section of the auxiliary fully developed simulation *Case* 1. These time signals comprised all three velocity components in the cross-sectional plane. The signals of five different durations t_s in terms of large-eddy-turnover-time h/u_τ are gathered. As outflow boundary condition gradients normal to the outflow cross-section have been set to zero. Irrespective of the size of the inflow time series (see Table I), all simulations were run for $16.8h/u_\tau$ and the inflow data were therefore recycled as many times as required, except for *Case* 6 (‘*time dependent*’) for which the inflow time signal size was just as long as the entire simulation time and no recycling was needed. Let us

DOI: 10.1002/fld

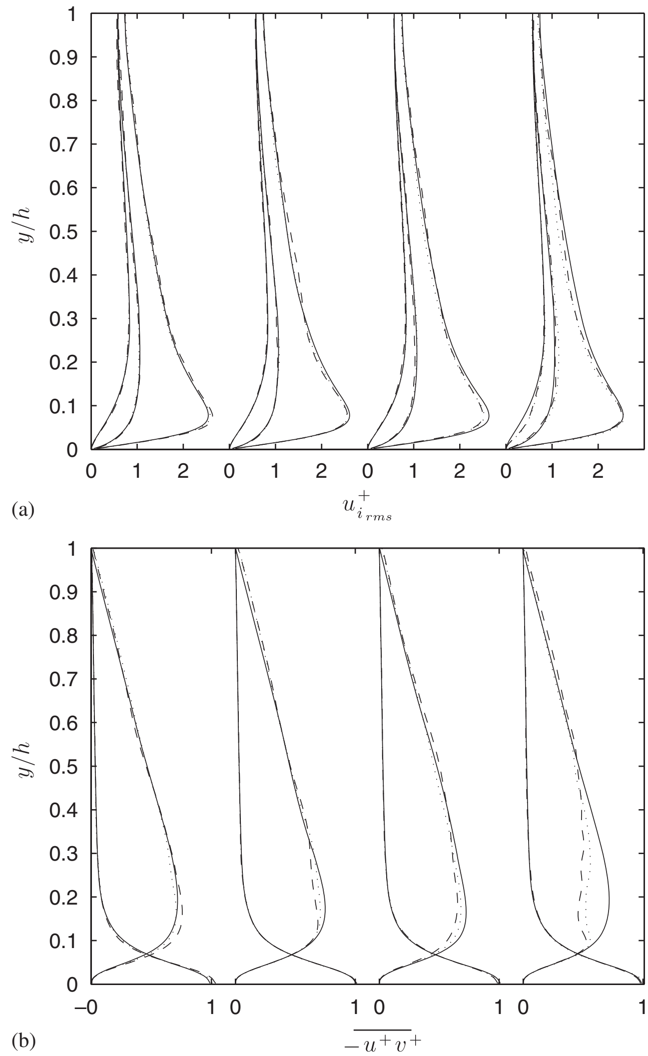

Figure 3. Turbulent statistics at the same cross-sections as in Figure 1: (a) turbulent intensities and (b) Reynolds and viscous shear stress. —, *Case* 1; – – –, *Case* 4; $\cdots$, *Case* 5.

emphasize that our *Case* 6 is essentially equivalent with the technique used in References [6–8]. This is the best choice in order to produce perfectly realistic inflow data. The penalty is that the precursor simulation inevitably must be run for equally long as the actual inhomogeneous flow simulation. Considerable savings can therefore be achieved by the recycling technique advocated by Li *et al.* [9]. The recycling strategy is therefore adopted also in the present study, but without the windowing technique used by Li *et al.* [9] in order to match the fields at the beginning and the end of the time sequence, thereby introducing a periodicity in the resulting flow field.

DOI: 10.1002/fld

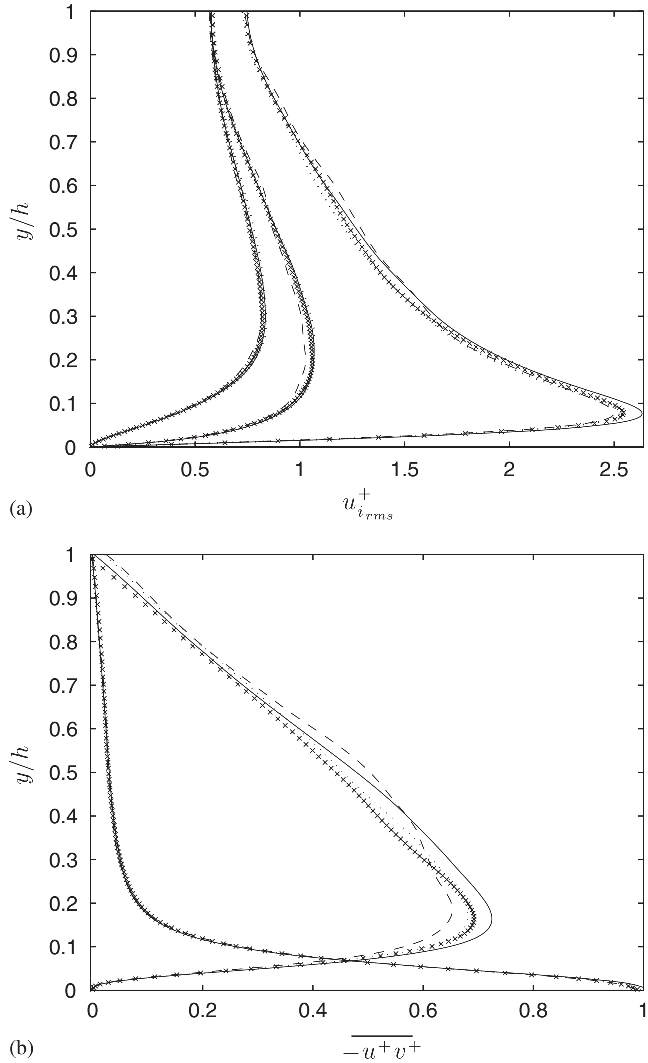

Figure 4. Turbulent statistics at $x/h=2\pi$: (a) turbulent intensities and (b) Reynolds and viscous shear stress. —, *Case* 1; – – –, *Case* 4; $\cdots$, *Case* 5; $\times$, *Case* 6.

3. RESULTS AND DISCUSSION

The different inflow cases show no differences when it comes to the mean velocity profile compared to the fully developed channel flow simulation (*Case* 1), except some variations for the shortest time series case (*Case* 2) as shown in Figure 1.

The turbulent statistics in Figure 2 indicate the unrealistic turbulent intensity and turbulent shear stress for the short time signals *Case* 2 and *Case* 3. The failure of *Case* 2 and *Case* 3 to

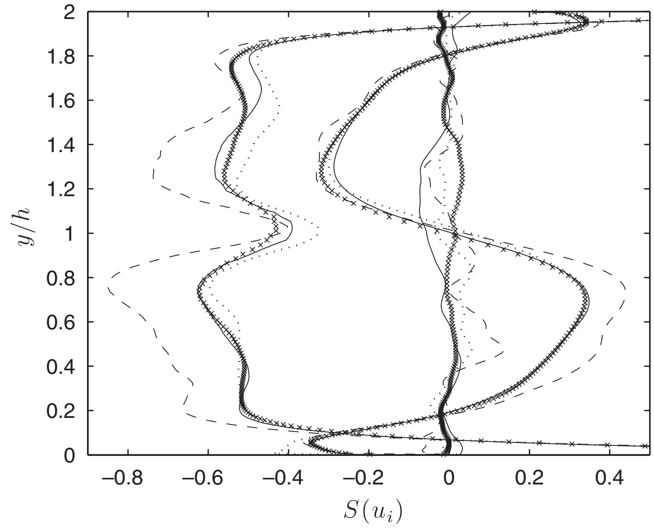

Figure 5. Skewness at $x/h=2\pi$. —, *Case* 1; – – –, *Case* 4; $\cdots$, *Case* 5; $\times$, *Case* 6.

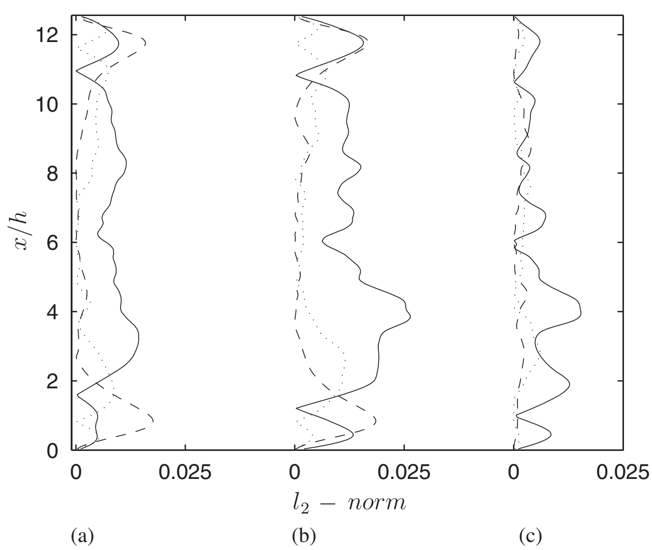

Figure 6. The l_2-*norm* of the residual turbulent intensities through out the channel: (a) l_2 (*Case* 6, *Case* 1); (b) l_2 (*Case* 5, *Case* 1); and (c) l_2 (*Case* 5, *Case* 6). —, u_{rms}; - - -, v_{rms}; $\cdots$, w_{rms}.

produce reasonable results is ascribed to the far too short time signal length $0.03h/u_\tau$ and $0.3h/u_\tau$, respectively. The inflow data do therefore not cover a representative sample of the large-eddy motions. For this reason results from *Case* 2 and *Case* 3 are excluded in the following. The rms-velocities and the turbulent shear stresses for the longer time series in Figure 3 exhibit a

DOI: 10.1002/fld

substantial improvement as compared with the corresponding profiles in Figure 2. The distortion at the last cross-section $x/h=4\pi$ in Figures 2(b) and 3(b) is believed to be due to reflections from the outflow boundary.

Figures 4 and 5 show just one plane halfway downstream of the channel. All the other cross-sections have been investigated and indicate similar behavior. The results show that *Case* 4 cannot be a good choice due to the large deviations in the high-order moments compared to the fully developed channel.

The results so far show that *Case* 5 closely approximates the results from the fully developed *Case* 1 using periodic boundary conditions even when the skewness is considered. The l_2-*norm* results in Figure 6 show that *Case* 5 compares favourably both with the fully developed *Case* 1 and the time-dependent *Case* 6. The l_2-*norm* is defined as

$$l_2(\text{Case}_i, \text{Case}_j) = \sqrt{\sum_{k=1}^{N_y} (\mathbf{u}_{\text{case}_i} - \mathbf{u}_{\text{case}_j})^T (\mathbf{u}_{\text{case}_i} - \mathbf{u}_{\text{case}_j})}$$

where

$$\mathbf{u} = \begin{bmatrix} u_{\text{rms}} \\ v_{\text{rms}} \\ w_{\text{rms}} \end{bmatrix}$$

4. CONCLUSIONS

Inflow boundary conditions generated as suggested by Li *et al.* [9] for free shear layers have been used for the first time to wall-bounded flows. As long as the inflow sampling period t_s is sufficiently long, i.e. $2.0h/u_\tau$, the potential periodicity introduced by the recycling of the finite time series vanishes due to the intense non-linear scrambling and the turbulent statistics are unaffected shortly downstream of the inflow plane. Recycling of finite-period inflow data is certainly a cost-effective strategy compared to running a precursor simulation of the same duration as the actual one. Substantially longer sampling is required for inhomogeneous flows than for homogeneous flows where sampling can be performed not only in time but also in the homogeneous direction(s). The expected cost savings is therefore particularly large for more complex flow configurations.

ACKNOWLEDGEMENTS

The present work has been supported by The Research Council of Norway through a grant of computing time (Programme for Supercomputing) and research fellowships for the first and second authors.

REFERENCES

1. Kristoffersen R, Andersson HI. Numerical transition to turbulence in plane poiseuille flow. *Numerical Methods in Laminar and Turbulent Flow* 1991; **7**:222.
2. Spalart PR, Watmuff JH. Experimental and numerical study of a turbulent boundary layer with pressure gradients. *Journal of Fluid Mechanics* 1993; **249**:337.
3. Lund TS, Wu X, Squires KD. Generation of inflow data for spatially-developing boundary layer simulations. *Journal of Computational Physics* 1998; **140**:233.

4. Johansson PS, Andersson HI. Generation of inflow data for inhomogeneous turbulence. *Theoretical and Computational Fluid Dynamics* 2004; **18**:371.
5. Keating A, Piomelli U, Balaras E, Kaltenbach HJ. A priori and a posteriori tests of inflow conditions for large-eddy simulation. *Physics of Fluids* 2004; **16**:4696.
6. Kaltenbach HJ, Fatica M, Mittal R, Lund TS, Moin P. Study of flow in a planar asymmetric diffuser using large-eddy simulation. *Journal of Fluid Mechanics* 1999; **390**:151.
7. Werner H, Wengle H. Large-eddy simulation of turbulent flow over and around a cube in a plane channel. In *Turbulent Shear Flows 8*; *Selected Papers from the Eighth International Symposium on Turbulent Shear Flows*, Durst F *et al.* (eds). Springer: Berlin, 1993; 155.
8. Meri A, Wengle H. DNS and LES of turbulent backward-facing step flow using 2nd- and 4th-order discretization. In *Advances in LES of Complex Flows*, Friedrich R, Rodi W (eds). Fluid Mechanics and its Applications, vol. 65. Kluwer: Dordrecht, 2002; 99.
9. Li N, Balaras E, Piomelli U. Inflow conditions for large-eddy simulations of mixing layers. *Physics of Fluids* 2000; **12**:935.
10. Manhart M. A zonal grid algorithm for DNS of turbulent boundary layers. *Computers and Fluids* 2004; **33**:435.

DOI: 10.1002/fld