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INVESTICE DO ROZVOJE VZDĚLÁVÁNÍ

Large Eddy Simulation of backward facing step

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Abstract: Large Eddy Simulations of backward facing step were performed. One of the difficulties of Large Eddy Simulation is correct representation of the turbulence on the inlet to the region. Therefore the simulations were done using different approaches to the inlet boundary condition. The impact of the choice of inlet boundary condition treatment on the fluid flow is consequently studied. It has shown, that using uniform velocity profile on inlet and even prescribing turbulent mean velocity profile without proper representation of turbulence fluctuations leads to unrealistic results. The only approach used in this work which gives sufficiently accurate solution is direct mapping of velocity from plane positioned behind the inlet back to the inlet.

1. Introduction

In the simulation of turbulent flow is the most important issue proper choice of turbulence model that will provide good representation of the flow. Another issue of great importance is specification of boundary conditions, especially inlet boundary condition. The velocity and another inflow data linked with turbulence prescribed by boundary condition should be consistent with chosen turbulent model. For the RANS simulations is sufficient to describe mean velocity profile and other turbulence variable (turbulent kinetic energy, ...) obtained from analytical solution or from experiments. This approach was justified in [1]. It was shown, that RANS model reach universal asymptotic behavior irrespective of the initial conditions. For Large Eddy Simulation, where the field on the inlet is turbulent, is situation more problematic. Usually the description of the flow is limited by knowledge of some statistical quantities such as mean velocity profiles and mass fluxes. In LES, the data generated by inlet boundary condition should consist of an unsteady turbulent velocity signal representing turbulence at the inlet. Ideally the simulation of upstream flow entering the computational domain will give good representation of the flow. However indefinitely extension in upstream direction is not possible because high computational cost. Therefore approximate inlet conditions must be specified. Many methods were developed in the past. Kaltenbach et al. [2] used recycling method. Turbulent fluctuations are specified by running precursor simulation, whose only role is to provide main simulation with accurate boundary data. Another approach is to add synthetic turbulence at the inlet. Lund et al. [3] modified inlet velocity field by adding a random term to all velocity components. Klein et al. [4] proposed digital signal processing procedure to remedy lack of large-scale dominance in the inflow data generated by the random method.

2. Governing equations

For the solution of the fluid flow in this article was chosen Large Eddy Simulation. The main idea of Large Eddy Simulation is to separate large scales (grid-scales) from small scales (subgrid-scales) to lower computational cost. The subgrid scales are modelled using subgrid model. The scale separation is done by applying low-pass filter operator on Navier-Stokes equation. If we apply the filter operator on Navier-Stokes equations we obtain filtered Navier-Stokes equations:

$$\frac{\partial \bar{u}_i}{\partial t} + \frac{\partial \bar{u}_j \bar{u}_i}{\partial x_j} + \frac{\partial \bar{p}}{\partial x_i} - \frac{1}{Re}\frac{\partial^2 \bar{u}_i}{\partial x_k \partial x_k} = \frac{\partial \tau_{ij}}{\partial x_j} \qquad (1)$$

For evaluation of subgrid stress tensor τ_{ij} is used Smagorinsky model:

$$\tau_{ij} - \frac{1}{3}\delta_{ij}\tau_{kk} = -2\nu_t \bar{S}_{ij}, \qquad (2)$$

where:

$$\nu_t = (C_S \Delta)^2 |\bar{S}|$$
$$|\bar{S}| = 1/2(\partial \bar{u}_j/\partial x_i + \partial \bar{u}_i/\partial x_j) \qquad (3)$$

3. Description of the test case

For testing of different approaches to the inlet boundary condition was chosen backward-facing step flow. This case of flow is good benchmark for validating various models because it contains massive separation and consequent re-attachment. Separation bubble on the wall opposite to the step could appear for some geometrical and flow parameters.

The geometry and flow properties was chosen according to the experimental study done by Fessler and Eaton [5]. The Reynolds number of the inlet channel flow was 13 800, based on the bulk velocity of 10 m/s and the channel half-width of 20 mm. The expansion ratio was 5/3. The flow parameters of the inlet channel and backward facing step flow are in table 1 and 2.

Channel half-width, h	20 mm
Channel length, 6h	120 mm
Channel bulk velocity, U_0	10 m/s
$Re_h = U_0 h/v$	13 800
u_τ, friction velocity	0.5 m/s
Kolmogorov length scale	170 µm

Table 1: Flow parameters of inflow channel

The computational mesh consists of 2.1 million hexahedral cells. The mesh is block-structured and becomes finer towards the wall in order to satisfy condition of y^+=1. The detail of the mesh near the trailing edge is in the Figure 1.

Step height, H	26.7 mm
Expansion ratio	5 : 3
$Re_H = U_0 H/v$	18 400
large eddy time scale, $5H/U_0$	12.7 ms

Table 2: Flow parameters of backward-facing step flow

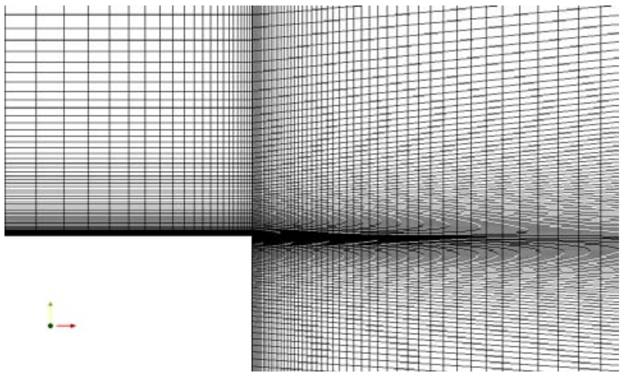

Figure 1: The detail of the mesh

4. Generation of inflow data

For the generation of the velocity on the inlet to the domain were used three different approaches. Let them denote as Case A, B and C. All cases have bulk velocity magnitude of 10 m/s.

Case A: Uniform velocity profile is prescribed on the inlet

Case B: Mean velocity profile of fully turbulent channel flow is prescribed on the inlet.

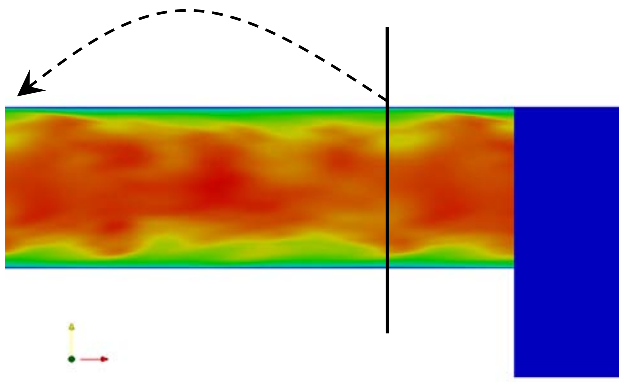

Figure 2: Scheme of data mapping

Case C: The velocity on the inlet is obtained by direct mapping of the velocity from the plane with 3h (60 mm) offset from the inlet plane. The schematic picture of the mapping is shown in the Figure 2 (the placement of the mapping plane in this figure is only schematic). For the flow initialization was used following procedure: First was done simulation of inlet channel only using periodic boundary condition. For faster transition to the fully developed turbulent flow was used forcing scheme based on Ornstein-Uhlenbeck process [6]. When the fully turbulent regime was reached then the results of this pre-simulation was mapped to the inlet channel of the backward-facing step geometry.

5. Results and discussion

In this section are described results obtained by various approaches to the inlet boundary condition. The simulations were started from zero velocity initial condition for cases A and B. The initial condition for case C could be seen in the Figure 2. The simulations ran for 0.5 s in order to allow development of turbulent structures in the domain. Then averaging was turned on and the simulations continued for another 1 s. This time was long enough to reach statistical steady state. The center of the coordinate system is positioned in the middle of the trailing edge.

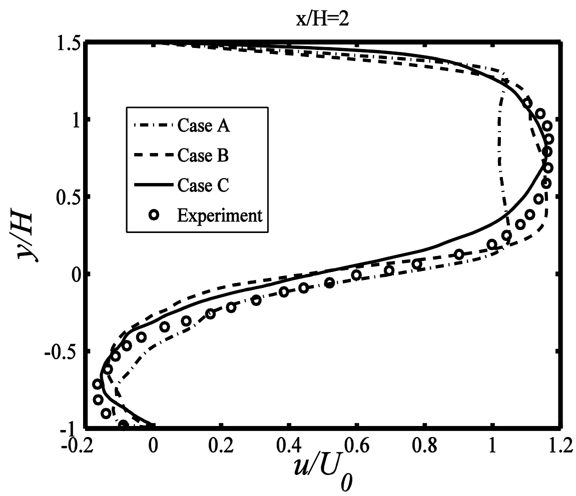

Figure 3: Velocity profile at position x/H = 2

In the figure 3 are velocity profiles in short distance from the step. It could be noticed that the uniform inlet velocity gives nonrealistic results. From the flatness of the profile above the step could be stated that the length of the inlet channel is not long enough in order to develop turbulent velocity profile.

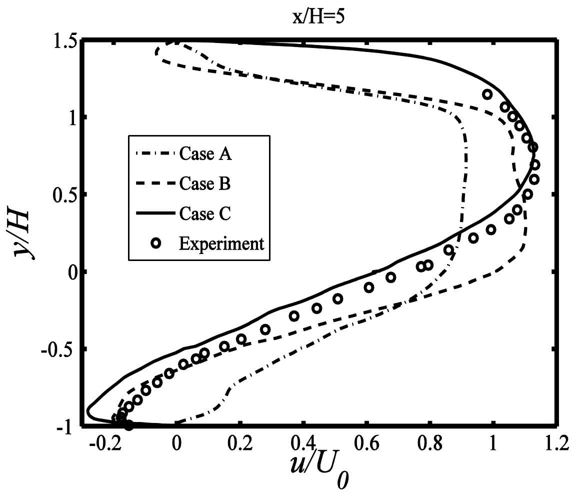

Figure 4: Velocity profile at position x/H = 5

Velocity profiles further from the step (x/H = 5) are in the figure 4. Negative values of velocity at the top of the domain predicted in cases A and B indicates that separation bubble has formed in this region. It is because of lack of wall-normal velocity fluctuation, which leads to absence of turbulent mixing mechanism and the main stream is bend down due the strong adverse pressure gradient. Case A also fails in prediction of re-attachment of the flow behind the step.

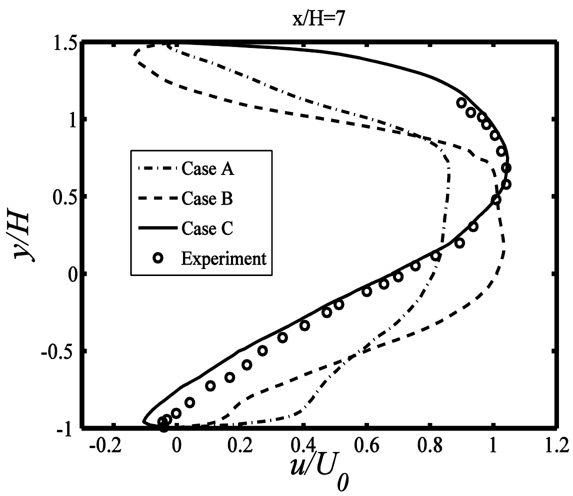

Figure 5: Velocity profile at position x/H = 7

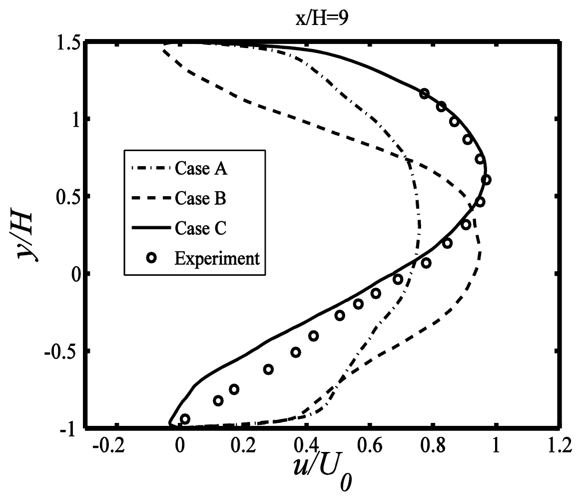

Figure 5: Velociy profile at position x/H = 9

Figures 5 and 6 show situation far behind the step. Case B also fails in prediction of re-attachment. On the other side, case C predicts re-attachment point quite well. Re-attachment point predicted by case C is at position x/H = 9.2 (experiment predicts this point at position x/H=8.4).

6. Summary

The Large Eddy Simulation of backward-facing step was done. The simulations were done for three different representation of inlet boundary condition: uniform velocity profile, turbulent velocity profile and direct mapping of velocity from plane behind the inlet. Only the last case gives realistic results because is capable represent also turbulence velocity fluctuation. This has shown critical for the accuracy of the simulation. The first two cases were not able to predict these fluctuations what resulted in the inclination of the incoming stream downwards and forming a separation bubble at the top of the domain. This is not in accordance with real experimental study. The inclination of the stream also affected the position of the re-attachment of the stream behind the step, the stream is re-attached too early.

The only proper way of representation of the inlet data presented in this work is running precursor simulation of the inlet channel using turbulence forcing and then mapping resulting fields to the main domain and direct mapping of velocity to the inlet. This is most complicated case but gives accurate results close to the experiment. The prediction of the re-attachment point could be improved by using more advanced subgrid model, for example some variant of localized Smagorinsky model [7].

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