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TURBULENCE FORCING SCHEME IN PHYSICAL SPACE BASED ON ORNSTEIN-UHLENBECK PROCESS

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Abstract. *New turbulence forcing scheme is introduced in this work. This scheme operates in physical space. The main idea of this scheme is generating a force in every time step of simulation in particular points in the computational domain and this force is than added to momentum equations. The force is generated using Ornstein-Uhlenbeck stochastic process. The main feature of this process is that the force generated in next time step is not independent on the previous value (the Ornstein-Uhlenbeck is so called Markov process). So there is a correlation in the history of the generated force. It is suitable to use this force for generating turbulence because of this correlation.*

The developed forcing scheme was tested on the case of turbulent channel flow. Method for solution was Large Eddy Simulation with subgrid kinetic energy subgrid model. The results presented in this work are for low Reynolds number channel flow. For this case are the results in a good agreement with DNS data.

1 INTRODUCTION

Numerical simulations of turbulence play nowadays an important role in the investigation of phenomena associated with turbulence. The two most commonly studied types of turbulence are freely decaying turbulence and forced turbulence. Forced turbulence is simulated using the turbulence forcing scheme. The main task of the turbulence forcing scheme is to supply the energy to the flow in order to prevent the gradual phasing out of turbulence. This energy is supplied for the smallest wavelength numbers (ie large scale) and shall be transported by the energy cascade to the large wave numbers, which leads to dissipation of energy through viscosity (Kolmogorov scale)[4] . Turbulence forcing also allows faster transition to a fully developed turbulent flow regime.

In the past there were developed many different turbulence forcing schemes. Eswaren and Pope[6] proposed stochastic spectral forcing scheme based on the generation of additional force, which is then added to the equations of motion. This force is generated for a specific range of wavelengths numbers. The generated force was obtained by the realization of independent random Ornstein-Uhlenbeck processes for each excited wave number. Overholt and Pope[3] on the contrary proposed a deterministic forcing spectral model. The small wave numbers are supplied with forcing energy. This energy depends on the velocity and forcing input parameters. This scheme shows a better representation of the energy containing vortices (scales) and smaller statistical variability of quantities than stochastic schemes. Aforementioned schemes have been proposed in the Fourier space. Hence the use of such schemes is conditional on solution of given problem in Fourier space. This can be in many cases very difficult, even impossible. Therefore, there was effort to develop forcing schemes in the physical space. Lundgren[5] proposed the so-called linear forcing. He added into equations of motion special forcing term whose size is directly proportional velocity. It turned out that this scheme achieves the same, if not better qualities, such as spectral schemes[1]. Another advantage of this scheme is relatively simple implementation to the solvers.

2 FORCING SCHEME

The forcing scheme proposed in this work is applied in physical space. In the computational domain are defined several forcing points. In these points is consequently generated forcing force. This generation is done in every time step. This force is than added to the momentum equations of motion. The force is obtained by realization of Ornstein-Uhlenbeck process. The Ornstein-Uhlenbeck process is stochastic diffusion process generated by Langevin equation which provides a reasonable approximation for modeling of velocity fluctuations[4]. The force generated in one point is independent on the forces generated in other points. Therefore the number of realizations of Ornstein-Uhlenbeck process is equal to the number of defined points.

The generation of the forcing force is governed by equation (1):

$$F_i(t+\Delta t) = F_i(t) - F_i(t)\frac{\Delta t}{T_{OU}} + \left(\frac{2\sigma_{OU}^2 \Delta t}{T_{OU}}\right)^{1/2} \xi(t), \tag{1}$$

where Δt is time step of the simulation, T_{OU} and σ_{OU} are two input parameters of the process. Parameter T_{OU} characterizes the integral time scale of the process, σ_{OU} defines the variance of the process. Function $\xi(t)$ is the random variable with normal Gauss distribution (zero mean, unit variance). The individual points are distinguished by the subscript of i.

The existence of two input parameters T_{OU} and σ_{OU} gives a wide range of variability of the Ornstein-Uhlenbeck process. There arises a question, how to set these parameters. Our suggestion is setting the integral time scale of the process T_{OU} equal to the integral time scale of the flow and the variance σ_{OU} equal to the bulk velocity.

3 DESCRIPTION OF THE TEST CASE

For validation of the results obtained by proposed turbulence forcing shceme was chosen the case of turbulent channel flow. The flow field simulated is a fully developed turbulent flow between two parallel walls. Hence, the flow is homogeneous both in the streamwise and spanwise directions and the statistics are dependent only upon the distance from the wall. DNS data for comparison was taken from DNS database of fully developed turbulent channel flow[2]. The particular configuration of the test case come from choice of channel half-width $\delta = 0.1m$ and kinematic viskosity $\nu = 10^{-6}m^2s^{-1}$.

The dimensions of the channel is: $5\Pi\delta$ in streamwise direction, 2δ in wall-normal direction and $2\Pi\delta$ in spanwise direction. For given kinematic viscosity $\nu = 10^{-6}m^2s^{-1}$ is bulk Reynolds number $Re_m = 3220$ and the Reynold number based on the friction velocity is $Re_\tau = 109$.

The computational grid consists of 60x25x24 cells. The spacing both in streamwise and spanwise direction is uniform. The mesh become finer towards the wall in order to capture turbulence generation in the near-wall region. On the wall is satisfied condition $y^+ = yu_\tau/\nu = 1$. The geometry and the computational grid is on the figure 1.

Boundary conditions in the area were set as follows: For $y = 0$ and $y = 2\delta$ is defined solid wall boundary condition. In the direction of the axis z (spanwise) is defined periodic boundary condition, in the direction of the x-axis (ie the entry and exit from the domain) is defined periodic Boundary condition as well. Points where the force is generated are uniformly distributed over the inlet area to the domain, picture 2. The initial conditions were uniform.

The proposed forcing scheme was implemented into solver *channelFoam* of turbulent channel flow using Large Eddy Simulation method. The solver *channelFoam* is part of the open-source CFD software package OpenFOAM-1.6.x. The LES computations were performed using top-hat filter and subgrid kinetic energy model as a subgrid model.

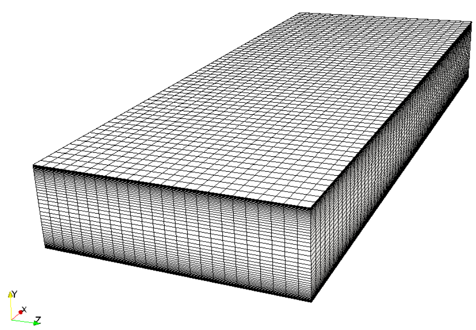

Figure 1: Geometry and mesh

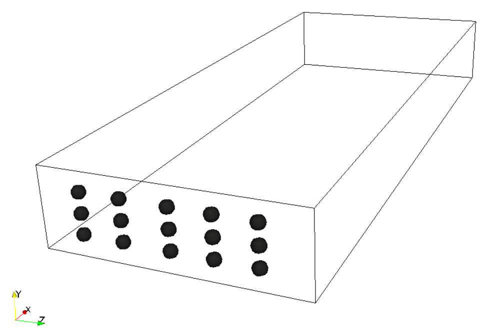

Figure 2: Location of forcing points

Parametric study investigating the influence of number of forcing points on the flow was done. It has shown, that the increase number of forcing points brought no significant improvement.

4 RESULTS

In the following paragraphs are given the results obtained with proposed turbulence forcing scheme. These results are represented by full line in the figures (labeled as Forcing), the dashed line refer to DNS data[2].

In the figure 3 is depicted velocity profile across the channel ($u^+ = u/u_\tau$). It could be noticed that the LES simulation with forcing slightly underestimates the velocity in the near-wall region.

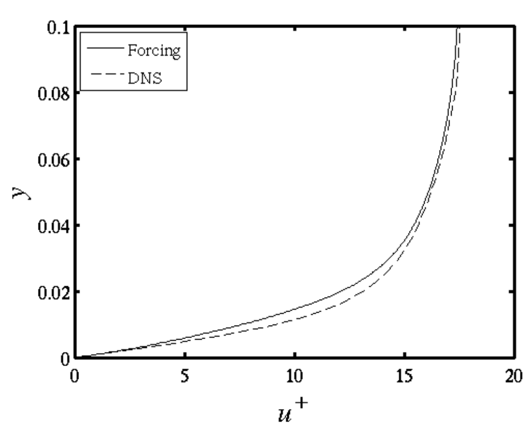

Figure 3: Velocity profile across the channel

Figures 4 and 5 show chosen turbulent statistics of the flow. The streamwise velocity fluctuation u^+_{rms} is underestimated for almost whole width of the channel. The wall-normal fluctuations are in the near-wall region overestimated, for $y/\delta > 0.5$ underestimated. The differences between LES simulation and DNS are not crucial.

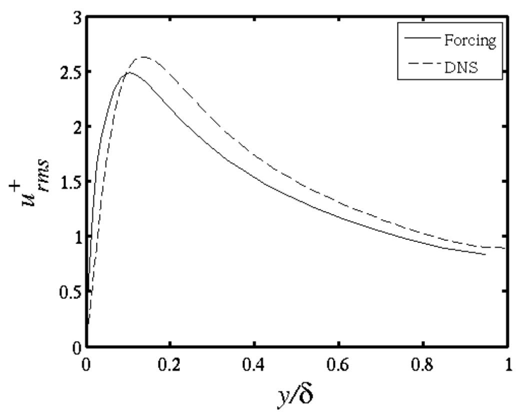

Figure 4: Streamwise velocity fluctuation

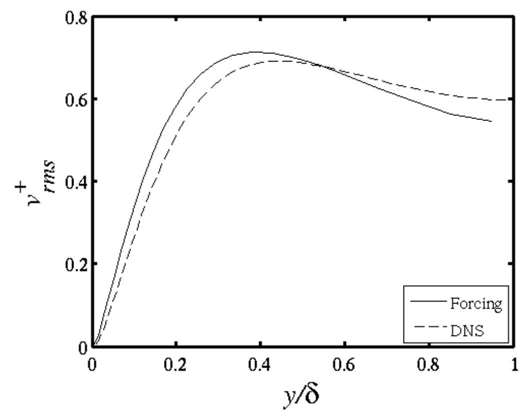

Figure 5: Wall-normal velocity fluctuation

In the figures 6 and 7 are evaluated power spectra in various distances from the wall. There is good agreement in the shape of the energy spectra with DNS data in both distances.

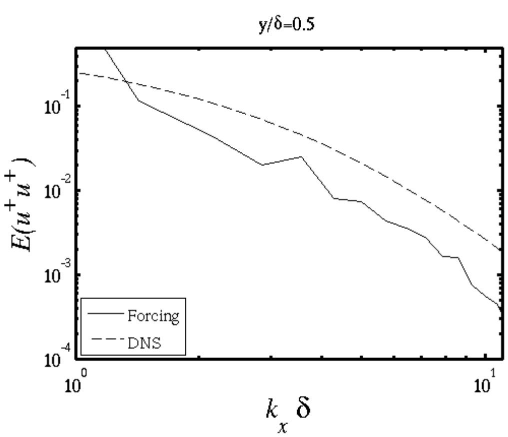

Figure 6: Energy spectrum in $y/\delta = 0.5$

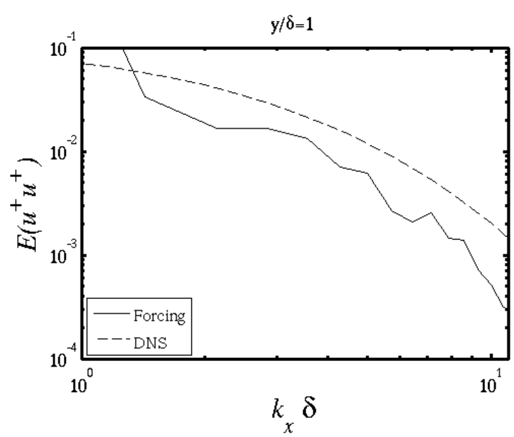

Figure 7: Energy spectrum in $y/\delta = 1$

5 CONCLUSIONS

New turbulence forcing scheme was introduced in this work. This scheme operates in physical space. The main idea of this scheme is generating a force in every time step in particular points in the computational domain and this force is than added to momentum equations. This force is generated using Ornstein-Uhlenbeck stochastic process. The main feature of this process is that the force generated in next time step is not independent on the previous value (the Ornstein-Uhlenbeck is so called Markov process). So there is a correlation in the history of the generated force. It is suitable to use this force for generating turbulence because of this correlation.

The developed forcing scheme was tested on the case of turbulent channel flow. Method for solution was Large Eddy Simulation with subgrid kinetic energy subgrid model. The results presented in this work are for low Reynolds number channel flow. For this case are the results in a good agreement with DNS data. The case of higher Reynolds numbers are currently computing and will be presented later.

The effect of number of forcing points was examined too. It turned out that the increase of these point has no significant effect on the turbulence. It was too examined the case when the forces generated in forcing points has only wall-normal component (the stream- and spanwise component are zero). In this case the results were almost identical so they were not introduced here.

6 ACKNOWLEDGMENT

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