TURBULENCE CHARACTERISTICS GENERATED BY 3D SPARSE GRIDS

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Abstract

The 3D Sparse Grid (3DS), Malik (2017a, b), has sparked interest in the turbulence community because of its potential to alter turbulence characteristics downstream of the grid. Here, we report on some recent results from DNS that demonstrate the performance of the 3DS in a conduit compared to the classical flat 2D Fractal Grid (2DF) arrangement Laziet and Vassilicos (2011). Some early results from 3DS experiments at the Max Planck Institute in Gottingen are also reported.

1 Introduction

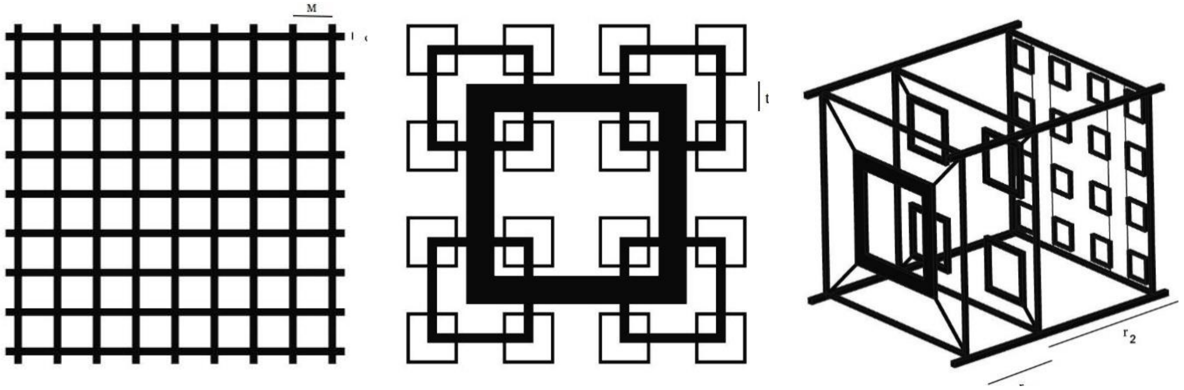

Figure 1. Left to right: (a) Regular grid (RG). (b) 2D flat fractal grid (2DF). (c) 3D sparse grid (3DS).

Grid generated turbulence is ubiquitous in turbulence experiments and have been studied for more than a century. However, until the early 1990's regular grids (RG), Fig. 1(a), with bars of constant thickness and open cells of constant width for flow passage have been used. In the 1990's a new type of grid with bars of different thicknesses and different lengths in a flat 2D fractal arrangement (2DF) was developed, Fig. 1(b), in which the different scales of turbulence are generated spontaneously in the same plane. The turbulence generated has different characteristics compared to the RG's, with the turbulence intensity peaking at a higher level Laziet and Vassilicos (2011).

Recently, a new advance in grid generated turbulence has been proposed by one of the authors, in Malik (2017a, b), called the Sparse 3D Multi-Scale Grid Turbulence Generator, or 3D sparse grid (3DS) for short. The 3DS goes further than the 2DF construction by separating each generation of length scale of turbulence grid elements in to its own frame in overall co-planar arrangement, Fig. 1(c), which produces a 3D 'sparse' grid system. Each generation of grid elements produces a turbulent wake pattern that interacts with the other wake patterns downstream. The length scale of the grid elements from frame to frame can be in any multiscale ratios, although a fractal pattern is a common choice.

Here, we report on the first set of Direct Numerical Simulations that have been carried out at King Fahd University of Petroleum & Minerals in Section 2. Some early results from experiments carried out the Max Planck Institute in Gottingen, are also reported in Section 3. We summaries in Section 4.

2 DNS Results

Direct Numerical Simulations (DNS) was used to simulate flow through turbulence generating grids in a conduit. The aim is to compare the turbulence characteristics from RG, 2DF, and 3DS grids.

The domain is a cuboid of dimensions $460.8 \times 115.2 \times 115.2\ d_{min}^3$ where d_{min} is the thickness of the smallest square. Thus, the height and width of the channel is $H = 115.2 d_{min}$.

The blockage ratios in the RG and 2DF is equal to 32% and the constant effective mesh size in the RG is $M_{eff} = 13.33\ d_{min}$. The bar of lengths in the RG is $115.2\ d_{min}$ with thickness 2.6 d_{min}, the same as in [3]. The bars in the 3DS has the same lengths and thicknesses as in the 2DF.

We non-dimensionalise all length scales by d_{min}.

The 2DF has non-dimensionlised lengths and widths $\{l_i, d_i\}$ in generations $i = 0,1,2$. The geometric ratio in the bar lengths is $r = 0.5$, and $a = 0.5$. Thus $l_0 = 57.6 = 0.5h$, $l_1 = 0.5 l_0$, $l_2 = 0.5 l_1$. For the bar thicknesses we have, $d_0 = 8.5$, $d_1 = 2.92$, $d_2 = 1$.

A time scale is defined by $t_2 = d_{min}/U_\infty$ where U_∞ is the inlet velocity set equal to 1. The 3DS has the same lengths and thickness as the 2DF, however each generation in held in a frame separated from the next by non-dimensional distances, $r_1 = x_1 - x_0 = 2d_0$, and $r_2 = x_1 - x_0 = d_0$, and $x_0 = 10$, where $x_i's$ are the non-dimensional x-coordinates of the *i'th* frame.

The solidity (blockage ratio) in the 2DF is $\sigma_{2F} = 32\%$, and the (effective) solidity in the 3DS is $\sigma_{3DS} = 32\%$; the solidity in the 3DS is defined to be the biggest in the threeframe system, $\sigma_{3Ds} = Max\{\sigma_1, \sigma_2, \sigma_3\}$.

To resolve down to the smallest scales a numerical grid size of one fifth of the thickness of the smallest bar is created, $\Delta x/d_{min} = 0.2$. This creates a grid of $N_x \times N_y \times N_z = 2304 \times 576 \times 576$. The RG and 2DF grids lie in the plane $x_0/d_{min} = 10$ downstream of the channel inlet. Periodic boundary conditions are applied on the walls in the y and z directions; and inlet-outlet boundary conditions were applied in the x-direction. The initial condition is a uniform inflow velocity $U_\infty = 1$. The Reynolds number is, $Re_{d_{min}} = \frac{U_\infty d_{min}}{\nu} = 300$.

OpenFOAM, (OFoam), an opensource CFD toolbox, is chosen for the simulation. OFoam uses finite volume discretization with Pressure Implicit Splitting of Operator Algorithm (PISO) scheme, and time discretization using a Backward Euler method. Gradient and Laplacian term discretization using Gauss linear method are performed. Divergence term discretization is done using Gauss cubic method which is a third order scheme. Interpolation and other terms are discretized using Gauss Linear schemes. The resulting linear systems are solved by preconditioned conjugate gradient method with diagonal incomplete Cholesky preconditioner for pressure solution whereas iterative solver is used with symmetric Gauss-Siedel as the smoother to calculate velocities. Tolerance is set at 10^{-6}. Simulation time step is $\Delta t = 0.015 d_{min}/U_\infty$ which corresponds to a Courant number of 0.75. Probes and pencils are placed at various locations and 100 complete field snapshots have also been recorded in the time range from $300 d_{min}/U_\infty$ to $600 d_{min}/U_\infty$. The flow statistics have been averaged over this time period.

Figures 2-4 show comparisons of turbulence characteristics from RG, 2DF, and 3DS grids from the current DNS simulations, where the distance between the successive frames in the 3DS are $r_1 = 2d_0$ and $r_2 = d_0$. The RG and 2DF plots are close to the results of Laziet & Vassilicos 2012 [3], who use an immersed boundary method Incompact3D, which validates the current OF-DNS for these calculations.

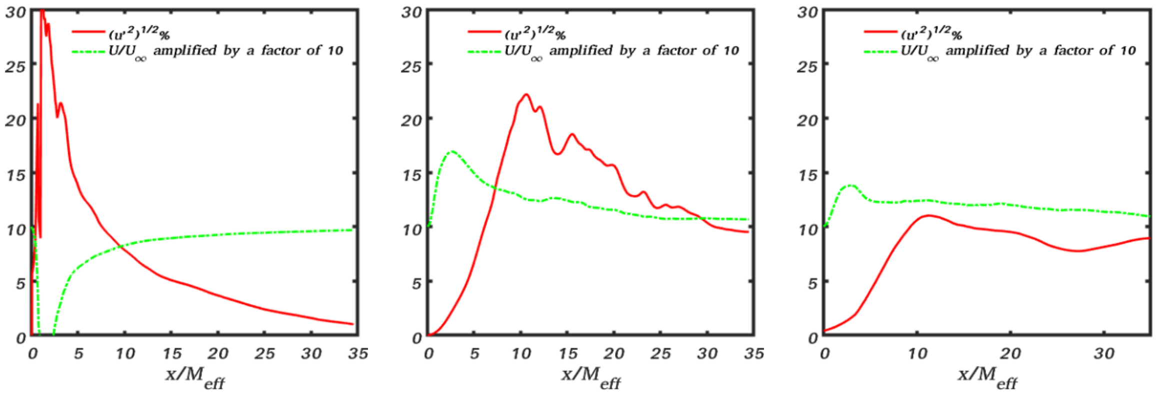

Figure 2. Turbulence intensity and mean velocity along the pencil at $(y, z) = (0,0)$ in the channel x-direction. Left to right: RG, 2DF, and 3DS.

Figure 2 shows plots of the turbulence intensity and the mean flow along the channel length in the x-directions through the central pencil at $(y, z) = (0,0)$. The mean flows in the 2DF and 3DS are close, but both are significantly higher than in the RG grid. The peak intensity from the 3DS is lower than from 2DF by about a half. After about $\frac{x}{M_{eff}} = 10$ the intensity in the 3DS remains lower than from 2DF, but higher than in the RG and also sustained for longer downstream than in the RG. The difference between the 2DF and 3DS is probably due to the lower blockage in the 3DS (15%) compared to the 2DF (32%).

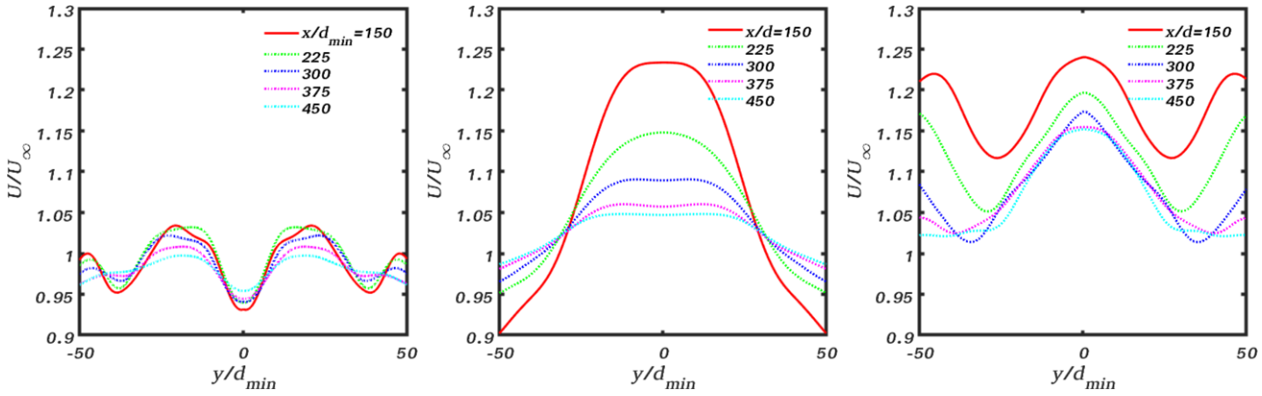

Figure 3. The mean velocity $U(y)/U_\infty$ in the y-direction at different stations along the channel length as indicated. Left: RG; Centre: 2DF; Right: 3DS.

Figure 3 shows the mean x-velocity along the y-direction, $U(y)/U_\infty$, at different stations along the channel. There is significant difference between the 2DF and 3DS grids. The 2DF grid produces essentially smooth non-oscillating profiles that peak and are uniform in the central region and eventually flattens out further downstream. The 3DS is closer to the RG profiles in so far as it shows an oscillating profile in the y-direction, however the peak intensity is comparable to the 2DF at around 1.25, but the RG produces a mean of about 1 at all stations along the channel. The 3DS profiles do not flatten out as fast as the 2DF, being sustained at a higher level further downstream.

The overall impression from these results is that the 3DS is approximately in between the RG and 2DF cases for the turbulence characteristics shown. However, it is crucial to remember that the blockage ratio in the 3DS is about half of the RG and 2DF so that the mass flow rate in the 3DS turbulence is doubled. To obtain the same flow rate in the RG and 2DF the pressure gradient would have to be doubled; so the mixing efficiency in the 3DS could still be greater in the 3DS.

3 Experimental Results

Experiments were carried out at the Max Planck Institute, Gottingen, on 3DS grids. A 3-generation 3DS turbulence generating grid was constructed, Figure 2, and placed in the wind tunnel at the MPI.

Mean flows of 1 m/s, 1.5 m/s, and 5 m/s were investigated. Probes were placed at various locations in the plane of the grid at different stations along the tunnel downstream of the grid. Recordings were at a rate of 10,000Hz, and the x-component of the velocity, $u(x, y, z, t)$, was recorded at each spot for 10mins, giving us ensembles of 6 million datapoints per recording.

Figure 2. The 3D Sparse Grid constructed at the Max Planck Institute, Gottingen.

The main quantities of interest are the correlations and the structure functions of higher order.

The turbulence time-correlation of the fluctuating velocity u'(t) is,

$$R_u(t) = \frac{\langle u'(s+t)u'(s)\rangle}{u'^2}.$$

The structure function of order n is,

$$S_n(t) = \langle [u'(s+t) - u'(s)]^n \rangle.$$

The angle brackets $\langle\cdot\rangle$ represent the ensemble averaging.

Figure 7 shows the correlations and the structures functions up to order 5 for the three flows. The time is non-dimensionalized by the $T_l = l/U,$ where $l = 1m$ is the scale of the 3DS grid.

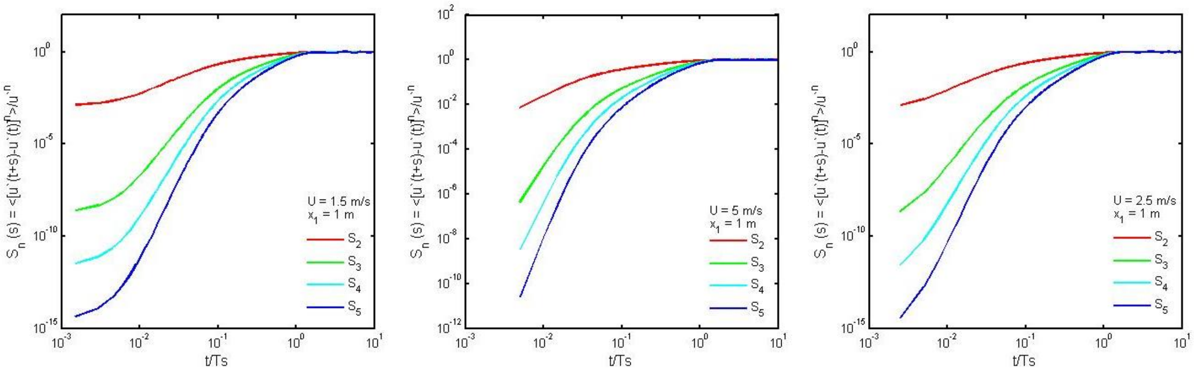

Figure 7. At $x = 1m$ downstream of the 3DS: (a) Correlation $R_u(t)$.
Structure functions up to order 5: (b) $U = 1m/s$, (c) $U = 1.5m/s$, (d) $U = 5m/s$.

4 Discussion

The 3DS has been investigated, and some comparisons with the Regular RG and flat fractal grid 2DF has been made. The 3DS admits a higher mass flow rate for the same pressure gradient because of the lower blockage ratio (solidity).

DNS was first validated against the previous work of Laziet & Vassilicos [3]. The DNS was then used to simulate 3DS with frame separations of $r_1 = 2d_0,\ r_2 = d_0$ and a blockage ratio of 15%, compared to 32% for the RG and 2DF. It was found that overall the turbulence characteristics generated by 3DS was generally in between the RG and 2DF grids; the peak turbulence intensities were lower than in 2DF, and downstream the intensities were also lower than in 2DF but higher than RG and were sustained for longer downstream.

A critical question is what happens if the blockage ratio of the 3DS is increased towards the 2DF value of 32%. Another is, does 3DS lead to greater mixing efficiency? These issues are currently under investigation numerically. In addition to the velocity field, we are looking at the vorticity field, the pressure field, and diffusing scalar fields. A parametric study for different r_1 and r_2, and for different 3DS blockage ratios are is being carried out at the current time.

Experiments at the MPI Gottingen were also carried out and high accuracy data has been collected. Some early results have been processed: correlations and structure functions of the velocity signals have been obtained. The aim is a multifractal analysis of the signal to investigate intermittency, and to obtain a comparison of turbulence intensities and mean flows at different locations in the channel from different types of grids. The findings will be reported in due course.

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