EXPERIMENTAL AND COMPUTATIONAL INVESTIGATION OF A FRACTAL GRID WAKE

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Abstract Fractal grids generate turbulence by exciting many length-scales of different sizes simultaneously. The interest in these grids finds its origin in the attempt to create ideal experiments on turbulence with well controlled conditions and very high Reynolds numbers [7, 4]. This interest has been further building-up since the surprising findings stemming from the experimental and computational studies conducted on these grids [2, 8, 3]. These results show that in contrast to the power-law decay of standard turbulence grids, the turbulence intensity in the wake of a fractal grid increases to reach a peak at some distance from the grid before it decays following an exponential law [2, 6]. In this work we present experimental and computational studies of the turbulent wake generated by a space-filling square fractal grid. The experimental work includes Particle Image Velocimetry (PIV) and hot-wire measurements. The numerical simulations are Delayed Detached Eddy Simulations (DDES) conducted using the open source package OpenFOAM [5]. Our goal is to provide a better insight on the turbulence generated by fractal grids and the suitability of DDES in characterizing it. To the authors knowledge this is the first time that DDES simulations are used to simulate the wake generated by a fractal grid. Additionally, the generated multi-scale turbulence will be used in future simulations as inflow condition. This will permit the use of more realistic inflow conditions to simulate flows over airfoils, wind turbine blades and whole wind turbines.

INTRODUCTION

In 2007, Hurst [2] assessed that fractal grids produce turbulence on a range of different scales. These scales influence each other and show very different properties than all previously documented turbulent flows. In this contribution, the wake of the flow through an N3 fractal square grid is simulated numerically (N is the number of iterations of the grid). The simulation is compared to experimental data acquired from PIV and hot-wire anemometry. Our main purpose is to validate our numerical simulations against the experimental results and to characterise the turbulence generated by fractal grids in terms of decay law and statistical quantities such as turbulence intensity, skewness and flatness. The characterization of such turbulent fields will assess the capabilities of DDES in reproducing the experimental results.

EXPERIMENTAL SETUP

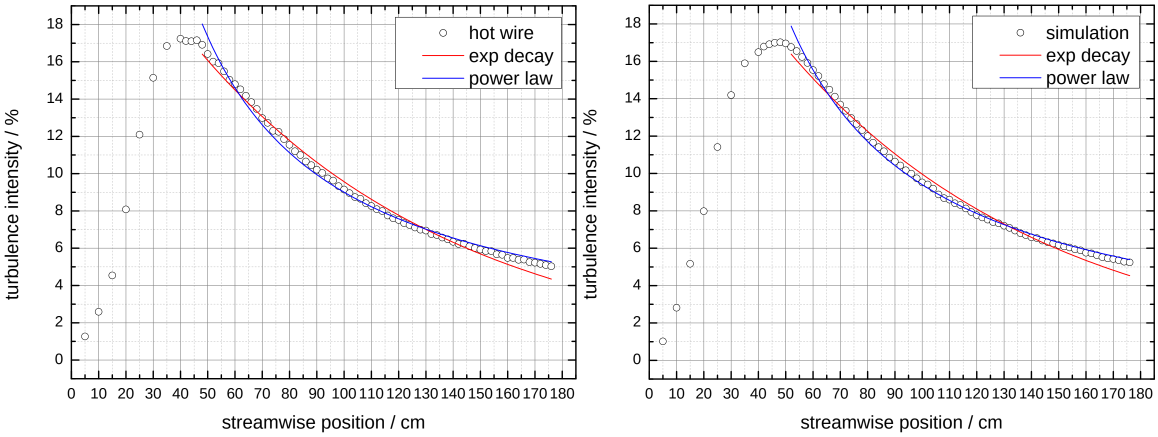
The experiments were conducted in a 2 m long closed wind tunnel with a cross section $T^2 = 25^2 cm^2$. The inlet velocity is 10 m/s and the flow velocities were measured by hot-wire anemometry. The hot-wires used are Dantec $2\mu m$ diameter and 1 mm long hot-wires. The sampling of the velocity was performed at 76 positions in the downstream window between 5 cm and 176 cm distance of the grid. The sampling frequency is 60 kHz and a total of 3.6 million samples were collected per measurement point, representing 60 seconds of measurements data. In addition Particle Image Velocimetry (PIV) is used for a quantitative and qualitative comparison with the CFD simulations. The PIV system used consists of a Nd:YAG double pulse laser system (λ = 532 nm, Quantel Brilliant B Twins, pulse energy 300 mJ) with a repetition rate of 10 Hz and a laser pulse delay of 60 μs. At each measuring point 3000 double images were taken by a CCD Camera (PCO 1600) and evaluated with the software PIVView using an interrogation window of 1 mm^2.

COMPUTATIONAL SETUP

The numerical simulation was set up analogous to the experiments in order to compare the results in a consistent manner. The fractal grid is simulated in a "computational" wind tunnel, where the flow-parallel boundaries are defined as frictionless walls and the computational domain begins at 2 m upstream distance from the fractal grid and covers a distance of 3 m downstream. The open source package OpenFOAM [5] is used for the simulations, which are run on the computer cluster of the ForWind Group [1]. The numerical mesh was generated using the built-in meshing tools blockMesh and snappyHexMesh [5].

RESULTS

The results are presented for the experimental and computational studies in terms of statistical turbulence properties and flow visualizations. The velocity distributions obtained by the numerical simulation and the experiments (not presented here) are compared, and a very good qualitative and quantitative agreement is found. The shedding behaviour in the wake of the fractal grid and the build up of the velocity on the center-line (the line where $y = z = 0$) is well captured by both investigation methods.



(a) (b)

Figure 1: The distribution the turbulence intensity along the streamwise direction at the center-line obtained for (a) the hot-wire measurements and (b) the computational simulations.

The numerical simulations are further compared to the hot-wire and PIV measurements by calculating statistical turbulence properties. The turbulence intensity ($TI = \sigma_u/\bar{u}$), the skewness ($S = \bar{u}'^3/\sigma_u^3$) and the flatness ($F = \bar{u}'^4/\sigma_u^4$) are calculated, along the streamwise direction, from hot-wire, PIV and CFD data and compared against each other. Here u' is the velocity fluctuation, $\sigma_u = \sqrt{\bar{u}'^2}$ the standard deviation and $\bar{u}$ the mean velocity. All quantities are plotted along the streamwise direction on the center-line. The turbulence intensity distribution obtained from the hot-wire measurements (Fig. 1a) increases as the turbulence is convected downstream up to a distance x_{peak}, where the turbulence intensity reaches its maximum value and decays further downstream. The CFD simulations (Fig. 1b) agree very well, although the turbulence intensity peak streamwise position is slightly shifted downstream in the CFD results. The turbulence intensity is fitted in the decay region with a power-law and an exponential-law. The power-law fits the experimental and the CFD data better than the exponential-law (it is also the case for the PIV data, not presented here). Further investigation of the turbulence decay, especially spatial averaging effects due to the dimensions of the sensors, and the analysis of the energy spectra will be conducted to investigate and explain these results.

The skewness and the flatness, are calculated for both the experiments and CFD and compared (not presented here). It is found that the CFD results agree well with the experimental results.

CONCLUSIONS AND OUTLOOK

The turbulent flow in the wake of an N3 fractal grid is investigated numerically and experimentally. For the first time, DDES simulations were conducted. The CFD simulations agree very well with the experimental results obtained by PIV and hot-wire measurements. The agreement is qualitative and quantitative and extends to the higher moments of the fluctuating velocities. The validation of the computational results is a first step in the process of the determination of the important scales and mechanisms governing the turbulent flow in the wake of fractal grids. The analysis will be extended to include the nature of the turbulence decay, and energy spectra analysis. Increment statistics using the data obtained from the hot-wire measurements and CFD simulations is also planed. The Markov properties of the data are going to be tested and depending on the results obtained a Fokker-Plank analysis will be conducted. These analysis will provide a better insight on the turbulence generated by fractal grids and the suitability of CFD models (DDES) to characterize this turbulence.

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