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THE DECAY OF TURBULENCE GENERATED BY SQUARE GRID AND SPACED SQUARE GRID

O. Ben Mahjoub ¹, A. Ouadoud ¹, J. M. Redondo ²¹ Department of Physics, Faculty of Polydisciplinary, University of Abdelmalek Essaadi, B.P 745, 92004, Larache, Morocco.² Department of Applied Physics, Polytechnic University of Catalonia, Jordi Girona, 08034 Barcelona, Spain

Abstract

Fractal grids generate multi-scale turbulent flows which interact with each other and form new multi-scales with different properties compared with those generated by classical grids. The goal of this work was to study the influence of geometry multiscale fractal on the generation and decay of turbulence by comparing the turbulence produced by a traditional fractal square grid **FSG** for short to that produced by a spaced fractal square grid **SFSG** for short with similar physical properties. The velocity measurements were performed in an open circuit suction type wind tunnel using a constant temperature hot wire anemometer at various positions in the x direction along the tunnel's center line and for three different Reynolds numbers Re_{L_0} based on the inlet velocity U_∞ and the length of the largest grid bar L_0 . It was found that the turbulence intensity decays with distance from the grid for SFSG. Whereas, for FSG at low Reynolds numbers the turbulence intensity shows the same behaviour as for SFSG but for higher Reynolds numbers the turbulence intensity increases to reach a peak at a distance x_{peak} from the grid and then decays. In the inhomogeneous region, for both types of grids, a scaling range spans over a decade with an exponent near, but not exactly, $k^{-5/3}$. In contrast, the length of the scaling range larger for FSG than for SFSG.

Keywords: Fractal grids, turbulence intensity.

1 Introduction

Fractal grids generate turbulence by simultaneously exciting many length scales of different sizes; The interest in these grids stems from the attempt to create ideal turbulence experiments with well-controlled conditions and very high Reynolds numbers [1, 2]. This interest has increased since the surprising discoveries resulting from the experimental and numerical studies carried out on these grids [3, 4, 5]. These results show that unlike the decay of the power law of standard turbulence grids, the intensity of turbulence in the wake of a fractal grid increases to peak at some distance from the grid before it collapses. Decays according to an exponential law [3, 6]. This work aimed to study the influence of multiscale fractal geometry on the generation and decay of turbulence, by comparing the turbulence produced by a FSG to that produced by a SFSG with similar physical properties. Velocity measurements were made in an open-circuit suction blower at various positions downstream of the two types of grids using a constant temperature hot-wire anemometer.

2 Fractal grids

The study of the turbulence generated by conventional grids has been accompanied by the introduction of a new generation of turbulence grids, called fractal grids. Fractal grids are the repetition of a specific pattern on different scales. They generate turbulence by creating different sizes of vortices with corresponding levels of interaction. The main interaction events occur when wakes of similar size meet and because the bars of a fractal grid have different sizes and are placed at different distances from each other, turbulence is generated from a range of wakes interacting at different places downstream. The smaller wakes meet and blend at positions closer to the grid than the larger wakes. The practical interest of this type of turbulent excitation concerns several fields of aeronautical and space application and also energy or environmental problems of noise reduction of mixers in combustion or for the numerical models of prediction of the dispersion of

pollutants in the atmosphere.

The particularity of this type of grid is that it is built on an iterative series of a basic pattern: an I , a cross, or a square, as illustrated in figure 1. These iterative series of patterns at different scales aiming to create a multiscale forcing of the flow, unlike regular mesh grids; each pattern generates turbulence with different properties. The SFSG pattern is the one used as the basis for this project. It was specifically discovered that this space-filling grid model with relatively low solidity can generate turbulence with high turbulence intensity and high Reynolds numbers, compared to the turbulence generated by regular grids; at the same flow velocity [3, 8].

Figure 1: Fractal grid patterns: (a) Cross pattern (b) I pattern (c) Square pattern.

3 Experimental Setup

In order to study the turbulence in the test vein, the FSG and SFSG were designed and fabricated with the number of fractal iterations N equal to 3, as shown in figure 2. The difference between the two types of grids is that SFSG has been designated such that each generation of length scale of turbulence grid elements is held in its own co-frame, in overall co-planar. This produces a sparse grid system whereby each generation of grid elements produces a turbulent wake pattern that interacts with the other wake patterns downstream. The spacing between each co-frame is $d = 0.5m$.

Figure 2: Schematics of the fractal grids used in the experiment: (a) FSG and (b) SFSG.

As can be seen in the figure 2, the FSG and SFSG have a pattern that repeats itself in a smaller and smaller way. They have different bars of different sizes. This allows turbulence to be generated by creating different sizes of vortices with corresponding levels of interaction. This type of grid can generate turbulence with an accumulating region of production and a region of decay. It should make it possible to achieve turbulent intensity and larger turbulence scales. The dimensions of the

first mesh are $L_0 = 0.441m$ and $t_0 = 0.042m$. Where L_0 is the length of the largest bar in the grid and t_0 is the thickness of the largest bar in the grid. The thickness and length ratios R_t and R_L of the grid in question are respectively 0.5 and 0.49. The solidity σ obtained for the entire grid is worth 20% which is relatively low compared to regular mesh grids ($\sigma \approx 34\%$). Its effective mesh M_{eff} equal to $0.3144m$. More details on the values of the parameters which characterize the FSG and SFSG used in this experiment are presented in table 1.

Parameters	Values	Parameters	Values
$L_0(m)$	0.441	$t_0(m)$	0.042
$L_1(m)$	0.2205	$t_1(m)$	0.02125
$L_2(m)$	0.11025	$t_2(m)$	0.0105
R_t	0.49	R_L	0.50
D_f	2	$M_{eff}(m)$	0.3144
$\sigma(\%)$	20	$d(m)$	0.5

Table 1: Parameters that characterize the FSG and SFSG used in the experiment with $N = 3$.

Figure 3: (a) Interior view of the wind tunnel, (b) SFSG

The measurements are carried out in an open-circuit suction wind tunnel installed at the laboratory of the Max-Planck Institute for Dynamics and Self-Organization in Göttingen (Germany), with a test section of $L_y * L_z * L_x$ ($Width = 1.5m$)*($Height = 1.5m$)*($Length = 10m$). The tunnel diagrams are shown in figure 3. The incoming airflow passes through a honeycomb, active grid; the shutters of the active grid are mounted side by side on vertical and horizontal axes, each axis is controlled independently by a drive connected to a motor. Fractal grids were installed in the wind tunnel after $1m$ from the active grid. Velocity fields were measured using a constant temperature hot-wire anemometer as this type of anemometer can provide the spatial and temporal resolution necessary to capture all relevant scales of the turbulent flow.

A single DANTEC probe was used on which is mounted a Platinum/Tungsten wire with a diameter of $5\mu m$ and a sensitive length of $1mm$. The probe was calibrated in place and positioned perpendicular to the direction of flow in the blower while varying the fan speed. Series of velocity measurements were taken at different positions downstream of the fractal grids, between $0.5m$ and $4m$ for the FSG and between $0.5m$ and $3.5m$ for the SFSG. 9.1 million data points were recorded for each position with a sample rate of $10kHz$, which represents 15 minutes of measurement data. The maximum flow velocity in the blower is approximately $11m/s$. The measurements were carried out using three different inlet velocities U_∞ at the inlet of the test stream: $1.5m/s$, $2.5m/s$ and $5m/s$. They reached measurement uncertainties in the order of ± 2

4 Results and discussion

Figure 4a shows the evolution of the mean velocity U_{mean} as a function of the distance downstream of the FSG on the central axis of the wind tunnel. For $U_\infty = 2.5m/s$ and $U_\infty = 5m/s$,

it appears that U_{mean} increases with the downstream distance up to $x = 1m$, after this distance U_{mean} decreases with the downstream distance. Excepting the $U_{\infty} = 1.5m/s$, U_{mean} decreases with increasing distance downstream. Figure 4b shows the evolution of the mean velocity U_{mean} as a function of the distance downstream of the SFSG on the axis of the vein. For different U_{∞} , it appears that U_{mean} increases with the downstream distance up to $x = 1m$ and after this distance U_{mean} decreases with the downstream distance. For the two type of grids, the decrease of U_{mean} is faster for the smallest values of U_{∞} .

Figure 4: The evolution of the longitudinal mean velocity along the wind tunnel's central axis for three different values of U_{∞} : (a) FSG and (b) SFSG.

Figure 5 represents the evolution of the turbulence intensity I_u along the wind tunnel's central axis for the two types of grids, the FSG and the SFSG for different U_{∞} . I_u increases with distance downstream from the FSG until it reaches a peak, as shown in figure 5a. The positions of the turbulence peaks are not constant and vary with U_{∞} , $x = 1.5m$ for $U_{\infty} = 1.5m/s$ and $x = 2m$ for $U_{\infty} = 2.5m/s$ and $U_{\infty} = 5m/s$. Beyond these positions, the turbulence intensity decreases to a minimum when $x = 3.5m$. On the other hand, it appears that I_u decreases downstream of the SFSG, as illustrated in figure 5b. For both grids, the turbulence rate decreases with increasing U_{∞} .

The figure 6, represents the evolution of the longitudinal integral scale L_x along the wind tunnel's central axis for the two types of grids for different U_{∞} . It appears very clearly that the longitudinal integral scale L_x increases with the distance downstream of the grid for the two types of grids. On the other hand, L_x increases with increasing U_{∞} , which is consistent with previous results of [3, 9]. On the other hand, L_x is greater for the turbulence generated by the FSG than for the turbulence generated by the SFSG.

Figure 7, shows the evolution of the longitudinal Taylor scale λ along the central axis of the wind tunnel for the two types of grids for different U_{∞} . We observe that for $U_{\infty} = 1.5m/s$ and $U_{\infty} = 2.5m/s$, λ decreases with the distance downstream of the two types of grids. However, for $U_{\infty} = 5m/s$, λ increases with the distance downstream of the two types of grids.

Figure 8a shows the evolution of the Reynolds number Re_{λ} as a function of the distance downstream of the FSG, along the central axis of the wind tunnel, at different U_{∞} . We observe that for $U_{\infty} = 2.5m/s$ and $U_{\infty} = 5m/s$, Re_{λ} increases with the distance downstream of the grid until reach its maximum value and then decrease. Re_{λ} reaches its maximum value at distances $x = 1.5m$ and $x = 2.5m$ downstream of the grid for $U_{\infty} = 2.5m/s$ and $U_{\infty} = 5m/s$ respectively. Whereas, for $U_{\infty} = 1.5m/s$, Re_{λ} decreases with the distance downstream from the grid. Concerning the

Figure 5: The evolution of the turbulence intensity along the wind tunnel's central axis for three different values of U_∞ : (a) FSG and (b) SFSG.

Figure 6: The evolution of the longitudinal integral scale along the wind tunnel's central axis for three different values of U_∞ : (a) FSG and (b) SFSG.

SFSG we observe that Re_λ decreases away from the grid for the three values of U_∞ , the results are illustrated in figure 8b. However, Re_λ is higher for turbulence generated downstream of the FSG than for turbulence generated downstream of the SFSG. Re_λ decreases rapidly downstream of the SFSG than downstream of the FSG.

The study of the energy spectrum of the turbulence is also important to verify that the turbulence is fully developed. The energy spectrum of the longitudinal velocity fluctuations at two positions downstream of the two types of grids were calculated. Figure 9 presents the compensated energy spectrum $E(k)k^{5/3}$ obtained by multiplying the spectral density by $k^{5/3}$ as a function of the dimensionless wave number $k\eta$, where η is the Kolmogorov length scale, at positions $x = 1.5m$ and $x = 3m$ downstream of the FSG and at positions $x = 1m$ and $x = 3m$ downstream of the SFSG for three different values of U_∞ between $2.5m/s$ and $5m/s$.

Figure 7: The evolution of the longitudinal Taylor scale along the central axis of the wind tunnel for three different values of U_∞ : (a) FSG and (b) SFSG.

Figure 8: The evolution of the Reynolds number along the central axis of the wind tunnel for three different values of U_∞ : (a) FSG and (b) SFSG.

The variation of the exponent k^m in the inertial range for the two types of grids is not very far from the prediction of Kolmogorov's $5/3$ law, it is always less than 1.2% for the different values of U_∞ and the positions downstream of the grid. We observe a behavior in scale law k^m on sufficiently large inertial range. The slope of the energy spectrum depends on U_∞ and the distance downstream of the grids, it increases with the distance downstream of the grids and with the increase in U_∞ . These values vary between $m = 1.54$ and $m = 1.62$ in the inertial range, they are close, but not exactly, to the prediction $k^{-5/3}$ of Kolmogorov. This deviation is attributed to the distance from the homogeneous and stationary state of the flow. We observe the effect of the increase in the speed U_∞ , causes on the one hand, an increase in the width of the inertial range, and on the other hand, the rise in the energy level large structures. Yet, the energy spectrum for the two grids do not show frequency peaks. This means that no coherent structure can come from the wake downstream of these grids.

Figure 9: Longitudinal energy spectrum compensated by $k^{5/3}$ at the central axis of the wind tunnel for three different values of U_∞ : (a) FSG at $x = 1.5m$, (b) FSG at $x = 3m$, (c) SFSG at $x = 1m$, and (d) SFSG at $x = 3m$.

5 Conclusions

The experimental study of the turbulent flow generated downstream of two types of fractal grids, one with a FSG and the other with a SFSG, producing a multiscale forcing through velocity measurements by a hot wire anemometer at constant temperature. Both types of grids have similar physical properties, one with FSG and the other with SFSG.

The main takeaways from this study are as follows:

- The rate of turbulence increases with distance downstream of the FSG until it reaches a peak; this trend is consistent with previous [3] results.
- The longitudinal Taylor scale λ decreases with the distance downstream of the two types of grids for $U_\infty = 1.5m/s$ and $U_\infty = 2.5m/s$. However, λ increases with the distance downstream of the two types of grids for $U_\infty = 5m/s$, which is consistent with previous results [3, 9].
- The integral length scale plays a primary role in determining the size of energetic vortices,

the geometry of the turbulence generator, and the scale at which the turbulence is forced. The longitudinal integral scale L_x increases with the distance downstream of the grid and with the increase in U_∞ for the two types of grid, which is consistent with previous results de [3, 9]. Whereas, L_x is greater for the turbulence generated by a FSG than for the turbulence generated by a SFSG.

- The Reynolds number Re_λ increases with the distance downstream of the FSG until it reaches its maximum value and then decreases. This trend is consistent with previous results for values of $Re_\lambda > 70$ [3, 10, 11, 12].
- The slope of the energy spectrum for the two types of grids depends on U_∞ and the distance downstream of the grids, it increases with the distance downstream of the grids and with the increase in U_∞ . This variation is always less than 1.2% even at distances close to the grids where the flow is non-homogeneous and the Kolmogorov hypothesis does not apply to this type of flow. Therefore, the use of the energy spectrum is not the best tool to study the large-scale properties of non-homogeneous flows.

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