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Generating atmospheric turbulence using passive grids in an expansion test section of a wind tunnel

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ABSTRACT

Generating atmospheric turbulence in wind tunnels is an important issue in the study of wind turbine aerodynamics. A turbulent inlet is usually generated using passive grids. However, to obtain an atmospheric-like flow field relatively large length scales ($L \sim 30$ cm) and high turbulence intensities ($I \sim 15\%$) need to be reproduced. In this work, the passive grid technique has been used in combination with a downstream expansion test section in order to investigate the generation of atmospheric like turbulence, with the possibility of varying both the turbulence intensity and the integral length scale of the flow field independently. Four passive grids with different mesh and bar sizes were used with four wind velocities and five downstream measurement positions. It was found that the flow field is isotropic and homogeneous for distances less than what is recommended in literature ($x/M \sim 5$). The effect of the expansion on the turbulence characteristics is also investigated in detail for the first time. The study confirms that by adding an expansion test section it is possible to increase both turbulence intensity and integral length scale downstream from the grid with limited impact on the overall flow quality in terms of anisotropy and energy spectra.

1. Introduction

The generation of controlled statistics of turbulence at the inlet of wind tunnel tests is of paramount importance for many aerodynamic applications. Research on bluff body aerodynamics (Bearman and Morel, 1983; Nakamura et al., 1988), turbulence decay (Comte-Bellot and Corrsin, 1966), turbulence interaction noise (Kim et al., 2016) or wind energy (Sicot et al., 2008) requires Free Stream Turbulence (FST) with a rather faceted spectrum of length scales and turbulence intensities to be generated at the inlet. Several approaches can be used for this purpose, such as grid generated turbulence, thermal driven turbulence, the use of cross jets, and actuated foils. While each of these methods has some advantages and disadvantages, grid generated turbulence is considered as the most effective and reliable source of a turbulent inflow for wind tunnel testing (Batchelor, 1953; Hinze, 1975). At least three families of grids are found in the literature: passive, active, and fractal grids.

The use of a passive grid (PG) has been the elected technique of generating turbulence at the inlet of wind tunnel tests since the first pioneering works on turbulence decay (de Karman and Howarth, 1938; Simmons and Salter, 1934; Taylor, 1935). Grid turbulence is generated by the shedding of vortices downstream of bars. The upstream quiescent flow undergoes a transition to a homogeneous and isotropic turbulent flow, characterised with slow rotating vortices which roughly scale to the size of the bars of the grid $L_u \sim b$ (Davidson, 2004). Once the flow is fully developed, turbulence decay dominates the statistics. The rate of decay has been set by Baines and Peterson (1951) and Vickery (1966) to -5/7, while Laneville (1973) has instead proposed a value of -8/9. Mohamed and Larue (1990) pointed out that two distinct regions of the flow exist, namely the far-field region, where turbulence decay is the main feature of the flow, and the near-field region, where production and a strong effect of the initial conditions are present (George, 2012). All PGs undergo such an analogous behaviour. Circular rods or square bars, arranged in square meshed or parallel arrays as well as perforated plates are used to build PGs with a variety of details, sizes and materials. Their effects have been systematically addressed by Roach (1987). However, the main classification of PGs is based on the dependence of the downstream turbulence on the Reynolds number, which is predominantly dictated by the shape of bars. Circular rods have a wake pattern that varies greatly with the Reynolds number or their roughness, while blunt bars feature a given separation at sharp corners (Bearman and Morel, 1983). Square bars compared to rectangular ones are more Reynolds sensitive, as flow re-attachment occurs more easily, modifying their wake (Nakamura, 1993). Smoothing or trimming the corners of square or rectangular bars has a limited impact on the turbulence characteristics (Nakamura et al., 1988). Although the use of rectangular bars is discouraged by some authors (Hancock and Bradshaw, 1983), others did not encounter any significant issues (Bearman and Morel, 1983; Nakamura, 1993; Nakamura et al., 1988; Vickery, 1966). The bar typology can be associated with

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different concepts for the construction of grids: Bi-planar grids (two sets of parallel bars placed side-by-side); Mono-planar grids (two set of overlapping parallel bars); A single set of parallel bars, either vertical or horizontal. Hancock and Bradshaw (1983) found that a bi-planar grid is preferable as mono-planar grids produce a highly unsteady non-uniform flow, possibly because of the larger separated region behind each intersection. Bearman and Morel (1983) argued that the non-uniformity of the flow decays in a much faster way for mono-planar grids than that of the bi-planar grid. However, the two grid options generate a similar turbulent flow (Nakamura et al., 1988; Roach, 1987). Nevertheless, the effect of the detailing of the grid is no longer apparent when the turbulent flow is fully developed. At what distance this occurs is still debated in research (Isaza et al., 2014). A mesh distance of $x/M > 10$ is considered by many authors (Bearman and Morel, 1983; Gartshore, 1984; Laneville, 1973; Saathoff and Melbourne, 1997; Vickery, 1966), but it is arguable whether this indication is sufficient to assume an independence of statistics with respect to the chosen detailing of the grid (Frenkiel et al., 1979).

The active grid (AG) concept uses a number of winglets mounted on a series of shafts, which rotate to generate a highly turbulent isotropic flow downstream of the grid (Makita, 1991; Makita and Sassa, 1991). This complicated setup has been further developed (Brzek et al., 2009; Cal et al., 2010) to produce integral length scales in the order of the cross-section size of the wind tunnel $L_u \sim H$ (Mydlarski and Warhaft, 2006). The turbulence characteristics can be adjusted by altering the rotating speed of the winglet-shafts (Cekli and van de Water, 2010; Kang et al., 2003; Larssen and Devenport, 2011). AGs have also been successfully used recently in research on wind energy (Maldonado et al., 2015).

The fractal grid (FG) concept has been recently developed to produce higher turbulence intensities and integral length scales up to $L_u \tilde{} H/10$ as well as limiting the distance from the grid at which the flow can be considered fully developed (Hurst and Vassilicos, 2007; Seoud and Vassilicos, 2007). A fractal grid of *Nth* order is created from a fractal generating pattern of complexity S, whose geometry is iterated N times. Mesh and bar sizes are varied accordingly. This technique is similar to that of the passive grid generation. However, a production region exists close to the grid where turbulence statistics develop toward a peak value. This does not occur for passive grids (Melina et al., 2016). The flow behind FGs resembles that of the near-field of passive grids. While the implementation of FGs for bluff body aerodynamics is being explored (Nedić and Vassilicos, 2015), PGs are more commonly used.

Thus far, many studies have investigated the effects of free stream turbulence for a variety of applications. However, only a few of them have attempted to address the effect of the turbulent statistics, taken independently of one another (Arie et al., 1981; Lee, 1975; Morenko and Fedyaev, 2017; Peyrin and Kondjoyan, 2002; Younis and Ting, 2012). If PG is the methodology of choice to generate inlet turbulence, a thorough study of the turbulence statistics at the inlet is sometimes only briefly mentioned, or omitted altogether. This might depend on the limited significance of the results, since low turbulence intensities (<5%) are normally available for large integral length scales (>20 cm) (Roach, 1987), while in the atmosphere higher turbulence intensities (>15%) are found (Antoniou et al., 1992; Kaimal et al., 1976). In order to achieve higher values for the turbulence intensity, the only possible way is to reduce the measuring distance from the grid, keeping the mesh and bar size sufficiently large to yield suitable length scales even close to the grid. However, the homogeneity and isotropy condition may not be achieved. It could be argued whether the distance limitation given in literature of $x/M > 10$ could be re-formulated for those studies not aimed at turbulence decay. Roach (1987) has warned that such limitations might be overconservative, suggesting that a homogeneous and isotropic, although not fully decaying, flow might be found closer to the grid.

Nevertheless, turbulence statistics of grid turbulence show a deviation from the condition of isotropy. Comte-Bellot and Corrsin (1966) confirmed the validity of the exponential decay law of de Karman and Howarth (1938), however they used a slight contraction of the wind tunnel section to achieve turbulence intensity isotropy. Although the inhomogeneity caused by the contraction does not affect the energy transfer of the decay rate, it was noted that integral length scale isotropy is more difficult to obtain. Later, several works have introduced a contraction section downstream of the PG. While most studies about the effect of a contraction on turbulent flows focus on the design of wind tunnels (Uberoi, 1956), some more recent works (Bereketab et al., 2000; Mish and Devenport, 2006; Swalwell et al., 2004; Wang et al., 2014) apply a contraction to adjust the isotropy for the inlet of bluff body aerodynamics applications. However, this approach causes a damping of turbulence downstream of the contraction, which in turn does not guarantee isotropy condition to be met for all statistics (Kurian and Fransson, 2009). Together with contractions, also expansion test sections, or diffusers, are broadly used in wind tunnels. Diffusers are placed as exit sections downstream of the working section, to create a pressure rise. Wide-angle diffusers are also needed upstream to allow for a contraction to be placed at the inlet to obtain a desirable steady flow (Bradshaw and Pankhurst, 1964). A diffuser is usually placed downstream or upstream of fans, as they need to be 2–3 times larger than the test-section to achieve a high quality flow field (Mehta, 1979). Diffusers have been tested regarding the performance in recovering pressure with reference to free stream turbulence (Hoffmann, 1981), but to the knowledge of the authors their use as a mean of modifying turbulent inlet statistics in wind tunnel testing is not yet reported in literature.

This paper introduces a novel method of varying turbulence statistics at the inlet of wind tunnel tests using an expansion section. The literature review has clarified that the generation of an atmospheric-like inflow is a challenging issue in the investigation of the effect of turbulence on bluff body aerodynamics, especially in obtaining large integral length scale turbulence ($L_u \tilde{} 0.3$ m) combined with high turbulence intensity ($I_u \tilde{} 15$ %). In the following, the grid generated turbulent flow upstream and downstream of an expansion test section is investigated. The aim is to show the possibility of modulating the turbulent flow to enhance statistics, without compromising them in terms of isotropy and gaussianity. The possibility of varying independently the various statistics is also assessed to understand their compatibility with atmospheric turbulence. Thanks to a thorough study of the turbulence decay mechanism, a simple empirical relation is proposed to predict the turbulence statistics at the outlet of the expansion. In Section 2, the experimental setup is reported together with the methodology to calculate results presented in Section 3. The feasibility of using an expansion together with grid generated turbulence has been assessed with the study of turbulence decay, isotropy, gaussianity, and energy spectra, and conclusions are given in Section 4.

2. Methodology

2.1. Experimental setup

The experiments were carried out in the multi-disciplinary wind tunnel of the University of Liège. The wind tunnel was operated in closed-loop configuration. The 1.50 m high and 1.95 m wide aeronautical test section (TS1) has a total length of 5 m. The 4 × 4 m contraction at the inlet nozzle, together with a series of honeycomb and a series of fine-grid screens, allows a remarkably low turbulence level (0.15%). The flow is accelerated by the 440 kW, 2.8 m diameter rotor that can drive the flow at velocity between 0.2 m/s and 65 m/s in closed-loop configuration. Fig. 1 shows a schematic of the test section. The 5 m long TS1 has a 5.1 m expansion to bind the aeronautical cross-section to the larger atmospheric boundary layer cross section TS2 which is 2.5 m wide and 1.8 m high. Therefore, a part of the TS2 section was also used for the measurements.

2.2. Design of passive grids

The design of a turbulent inflow to be generated with a PG requires a