The use of active grids in experimental facilities

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Abstract Active grids allow for the turbulence in experimental facilities to be tailored through a broad range of turbulence intensities and Reynolds numbers. This work provides an overview of the active grids that presently exist around the globe as well as advances in turbulence research that are a result of their use. Focus is placed on homogeneous turbulent flows, turbulent boundary layers, and model testing.

1 Introduction

Over the last 27 years active grids have become increasingly popular tools for generating bespoke turbulence in experimental facilities. This is evidenced by the recent review by Mydlarski [22]. The most popular type of active grid is the so-called 'Makita'-style active grid, named after the originator of its design [18]. A 3D-model of this type of grid is provided in Fig. 1. Generally, a Makita-style active grid is composed of a mesh of rods that are rotated by stepper motors. Each rod has a series of 'wings' mounted to them. By rotating the rods of the grid in different patterns, a transient blockage can be made at the inlet of a flow facility. Downstream of the grid, the flow develops into turbulence with higher turbulence intensities (u'/U) and Reynolds numbers ($Re_\lambda = u'\lambda/\nu$) than those achievable with classical passive grids, which are typically square meshes [12; 18; 22].

A list of the Makita-style active grids that are known to the author is provided in Table 1. Here, the year given to each grid is the year of the first journal paper associated with it. The table illustrates that active grids had a modest beginning, with only three grids in two different labs in the 1990s, followed by two more grids in the 2000s. However, from 2010 on we have seen an explosion in the number of grids world-wide. With this came a series of different modifications and developments to

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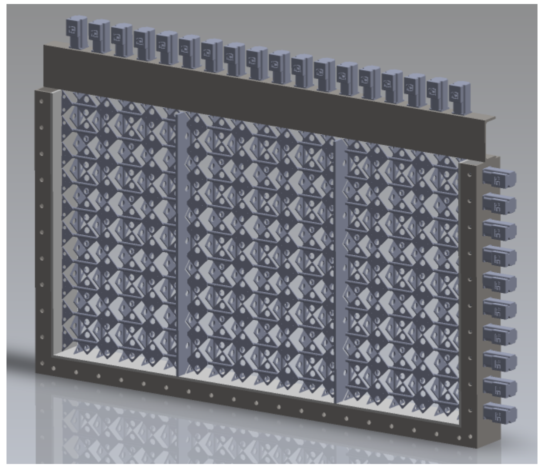

Fig. 1 Model of the active grid under construction at the Norwegian University of Science and Technology.

Makita's original design. For instance, Hearst and Lavoie [12] introduced the idea of having a double-bi-planar grid, where wings were mounted on a forward and aft mesh in an alternating pattern. In this way each wing was decoupled from those immediately adjacent to it. A similar idea was adopted by Kröger et al. [15] who instead split their axis along the centre of the grid so that the left and right sides (and top and bottom) were decoupled from each other. This idea was taken a step further at the Max Planck Institute in Göttingen where a grid was developed with each wing being independently controlled [1; 8].

While the first active grid studies were focussed on producing and studying high-Re_λ homogeneous, isotropic turbulence (HIT) [18; 23; 24], active grids have also been used more recently to investigate turbulent boundary layers (e.g., [29; 5]), and the effect of turbulence on other objects (e.g., [11; 28]). This work identifies the breadth of possibilities for using active grids in modern turbulence experiments.

2 Homogeneous turbulence

The original use of the active grids was to produce HIT [18; 23; 24]. Mydlarski and Warhaft [23; 24] used their grids to look for the Re_λ where a clear $k^{-5/3}$ inertial range in the velocity spectra emerged. They ultimately found that while there was an approach to this state, $k^{-5/3}$ was still not reached for the velocity spectra by $Re_\lambda = 731$, while a scalar approached the asymptotic state much faster. Later, detailed parametric studies on how to use an active grid to produce high-Re_λ HIT were conducted by Larssen and Devenport [16] and Hearst and Lavoie [12]; the latter is the most extensive parametric study to-date and builds on the results of the former. It was shown that a 'fully random' mode of operation, where each rod is actuated with randomised velocities and periods of rotation, is most suitable for

Table 1 List of different Makita-style active grids around the world with the studies that introduce them. While this list is intended to be exhaustive, it is possible some grids have been missed.

Study	Year	Institute	Country	Medium	M [mm]	Grid	$Re_\lambda^{\max}$	Notes
[18]	1991	Toyohashi U of Tech	Japan	Air	46.7	15×15	387	a
[23]	1996	Cornell U	USA	Air	50.8	8×8	473	
[24]	1998	Cornell U	USA	Air	114	8×8	731	
[26]	2002	U of Twente	Netherlands	Water	37.5	12×12	198	b
[13]	2003	John Hopkins U	USA	Air	152	7×5	716	
[3]	2010	TU Eindhoven	Netherlands	Air	100	7×10	870	
[14]	2011	ForWind Oldenburg	Germany	Air	110	9×7	2243	
[16]	2011	Virginia Tech	USA	Air	210	10×10	1362	
[20]	2011	Cen. Res. Inst. Elec. Pow.	Japan	Air	50	20×20	–	
[32]	2013	U of Florida	USA	Air	133	7×7	622	
[1]	2014	Max Planck Inst. Göttingen	Germany	Air, SF_6	115	13×11	1500	c
[25]	2014	CNRS Grenoble	France	Air	93.75	8×8	400	
[4]	2015	City College NY	USA	Air	50.8	11×15	339	
[12]	2015	U of Toronto	Canada	Air	80.0	15×10	486	d
[5]	2016	U of Southampton	UK	Air	81.0	11×7	760	
[17]	2016	Lehigh U	USA	Water	101.6	5×5	–	
[19]	2017	U of California Irvine	USA	Air	30.0	8×8	717	
[7]	2017	Georgia Tech	USA	Air	24.1	6×5	1242	
[30]	2017	Indian Inst. Tech. New Dehli	India	Air	69.0	10×10	206	
[33]	2017	New Mexico State U	USA	Air	190	6×6	–	
[27]	2017	Stanford U	USA	Air	100	8×7	–	
[15]	2018	ForWind Oldenburg	Germany	Air	140	20×20	14000	e
[31]	2018	Friedrich-Alexander U	Germany	Air, Oil	100.0	6×4	520	c
[21]	2018	Indian Inst. Tech. Madras	India	Air, He	32.5	8×8	96	
		NTNU	Norway	Water	100	18×10	–	
		U of Wyoming	USA	Air	101.6×71.12	10×10	–	d, f

(a) First Makita-style active grid made.
(b) First active grid in water.
(c) Every wing of the active grid is independently controllable.
(d) Made with two planes so that adjacent wings are decoupled.
(e) Physically the largest active grid in the world. Each axis is split in two along the centreline.
(f) The aspect-ratio of the wings in this grid is not one, i.e., each element of the mesh is a rectangle.

producing HIT without artefacts [12; 16]. Furthermore, the active grid parameters that give the greatest control authority over the produced flows are the rotational rate of the wings, the bulk Reynolds number, and the blockage of the wings [12]. The double-bi-planar design used by Hearst and Lavoie [12] ultimately did not result in an obvious benefit over the traditional Makita-style grids other than marginally improved homogeneity. They also tried to correlate different groups of wings to adjust the integral scale in the flow, but did not succeed. Interestingly, Griffin et al. [8], using a more advanced grid where every wing was independently controlled, were able to keep u'/U approximately constant while changing the integral scale by correlating different groups of wings.

3 Boundary layers

More recently, active grids have been used as a tool to investigate turbulent boundary layers (TBL). Sharp et al. [29] used an active grid to produced free-stream turbulence (FST) above a TBL, and found that increasing u'/U resulted in an increase in $Re_\tau = U_\tau \delta/\nu$, and that the boundary layer still exhibited much of the traditional TBL phenomenology. This was investigated further at the University of Southampton through a series of works [5; 6; 9] that effectively showed that flows resembling high-Re_τ TBLs, in particular their amplitude modulation characteristics and their spectrograms, can be emulated in standard laboratory facilities by adding FST. Hearst et al. [9] later provided a model that allowed for the prediction of the complete spectrogram in these flows based on only measurements of the FST spectrum, δ and U_τ.

The above inspired Hearst et al. [11] to use an active grid to modify a TBL such that the same shear was produced while u'/U was changed to study the wake of a wall-mounted cube immersed in a TBL. This was the first study whereby shear and u'/U were decoupled in this way, and it was made possible by the active grid. Adapted results from [11] are provided in Fig. 2 where it is shown that increasing u'/U at the cube height results in a shorter wake. The idea of separating the effects of shear and u'/U was later taken one step further by Hearst and Ganapathisubramani [10] who devised a series of active operational modes that could produce homogeneous shear flows with constant shear and varying u'/U or constant u'/U and varying shear.

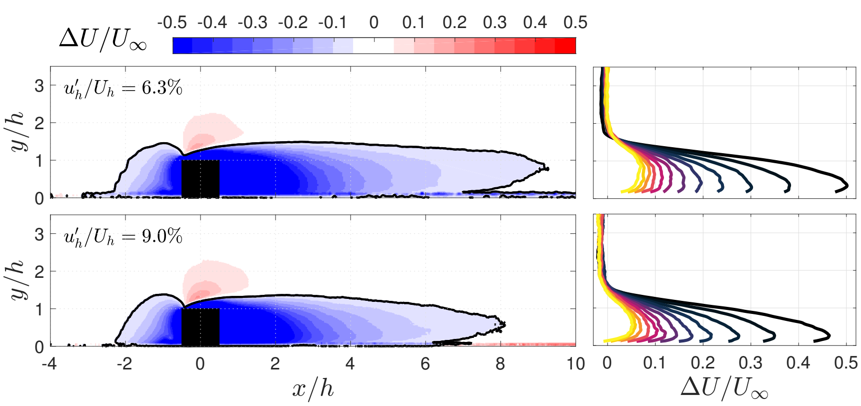

Fig. 2 Centreline of the wake of a cube immersed in a turbulent boundary layer that is subjected to free-stream turbulence. The FST is used to adjust u'/U at the cube height while keeping shear constant so that the effects of u'/U can be assessed independently of shear. Data adapted from [11].

4 Model testing

Most recently, active grids have been used to investigate the impact of FST on various models and bodies. For instance, the University of Florida has developed an active grid to test micro air vehicles [32] and Stanford has developed one for animal flow experiments [27]. However, the wind turbine community has really taken hold of this idea. This area is lead by ForWind Oldenburg, John Hopkins, and Portland State. Active grids have been used to study the effects of FST on individual wind turbines [28; 15; 33] as well as model wind farms [2]. There has been a particular emphasis at ForWind on producing turbulent flows that emulate the gusting nature of atmospheric flows, c.f., [14; 15]. The active grids thus allow for the simulation of real atmospheric conditions not otherwise achievable in experimental facilities, bringing us one step closer to both understanding the fundamental mechanisms in these flows, and performing tests in relevant conditions for field operations.

5 Concluding remarks

Active grids have solidified their place in modern turbulence experiments having been used for studies of decaying turbulence, turbulent boundary layers, and model testing. It seems, in fact, that most new turbulence facilities are built with the ability to add an active grid. Thus, I hope this overview has been useful for anyone seeking to implement such a system in their own facility and has helped point them in the direction of relevant previous works.

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