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GENERATING TURBULENCE USING PASSIVE GRIDS IN WIND TUNNEL TESTING

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ABSTRACT

This paper reports on a wind tunnel experiment on a wind turbine aerofoil under turbulent inlet. Urban Wind Energy is considered as a promising way of harvesting wind energy in built areas, hence slashing infrastructural wind energy costs. Effective positioning strategies are needed to maximise the performance; however, the role of turbulent inflows is not clear. In particular, the role of turbulent length scales is difficult to assess. In this work, the DU96w180 wind turbine aerofoil is investigated regarding its aerodynamic performance under varying inflow turbulence structures. Particular attention is given to the stall mechanism, hence the angle of attack of the blade is varied accordingly $0<\alpha<45deg$. Inlet turbulence is created by means of passive grids, with various geometrical setup, in order to obtain a wide range of turbulent structures. In order to test the effect of large scales, two chord length for the model are chosen $c=0.125\div0.025m$ in order to maximise the length-to-chord ratio L/c.

NOMENCLATURE

α	=	Angle of Attack [deg]
β	=	Porosity [-]
c	=	Chord length of aerofoil model [m] | characteristic length [m]
d	=	Grid bar size [m]
FST	=	Free Stream Turbulence
I	=	Turbulence intensity [-]
L	=	Integral length scale of turbulence [m]
M	=	Grid mesh size [m]
$\mathcal{R}e$	=	uc/v Reynolds number
UWE	=	Urban Wind Energy
WT	=	Wind Turbine
x	=	Distance between model and grid [m]

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INTRODUCTION AND BACKGROUND

Urban Wind Energy (UWE) is accounted as a suitable way of harvesting more wind energy in a more cost-efficient way [1]. However, the aerodynamics of wind turbines (WTs) located in built areas is challenging because of several issues, e.g. the statistics of the wind at the inlet and the response of WTs to such turbulent inflows. Based on these issues, the positioning of WTs within built premises is the main concern in UWE [2]. Supposedly, a suitable location for harvesting wind is at those spots of the urban environment, where the mean wind velocity is maximised, while the fluctuating wind is minimised [3]. However, this statement might find its origin in the tendency of replicating standard wind climate conditions [4], rather than reliable results, showing the actual performance with varying position, excluding limited literature focusing on the power output, rather that the aerodynamic performance [5].

This work will focus on the aerodynamic response of WTs to turbulent structures at the inlet. In fact, it is normally agreed that turbulence at the inlet is not a governing parameter for the aerodynamic performance. This important statement is largely accepted in the aeronautical field. Miley [6] pointed out that aerofoils are only sensitive to turbulence, if the inflow integral length scale is comparable with the boundary layer thickness. Wind Turbine aerodynamics has internalized this assumption, then Free Stream Turbulence (FST) supposedly has an effect only on the unsteady variation of the real angle of attack α, therefore turbulence is neglected in experiments and simulations [7]. The integral length scale of turbulence is then accounted as the reason, why atmospheric turbulence, which is characterised by large scales, has no role in the aerodynamic performance.

However, this assumption is invalidated for WTs for a twofold reason: (i) when placed in built premises, but also in clusters or in ducts, the turbulent inflow is not comparable to atmospheric winds, as usually provided with smaller scales; (ii) the understanding of the effects of turbulence on WT blades is directly related to bluff body aerodynamics, as WTs experience stall, which is affected by turbulence.

Numerous experimental studies have been performed to investigate the effect of either turbulence intensity or length scale of inflow turbulence on bluff bodies [8]. Although the literature still shows incongruences, important results are available for various basic bluff bodied shapes, but also for engineering applications as wind turbine blades [9]–[11]. Most works only correlate the aerodynamic performance with the turbulence intensity of the inflow, either disregarding the effect of the length scales, or giving a marginal interpretation of their importance. The reason for that is the difficulty in varying the range of the length scale L to characteristic dimension c ratio, while fixing the other statistics. Moreover, it is difficult to obtain range of scales larger than $L/c \leq 1.5\div2$. Therefore, the research is not directly applicable to atmospheric flows, which experience much larger integral scales. Nonetheless, urban flows are rather local flows characterised by signature turbulence in wakes or shear layers of buildings and other obstacles, hence the negligibility of turbulence is not a trivial assumption [12].

Bearman & Morel [8] have shown that free stream turbulence (FST) affects considerably both the mean and unsteady behaviour of separated shear layers of bluff bodies. In particular, the surface pressure is affected by a shift towards the separation point in both the mean, fluctuating and peak pressure statistics. This finding is confirmed also by Nakamura & Ozono [13], who stress out the role of the turbulent length scales. In particular, it seems that turbulence has a noticeable effect for $L/c \leq 5$, then approaching the smooth flow behaviour for higher scales. Li and Melbourne [14] used a large range of grid meshes and distances for a set of square prisms, noting that the effect of length scales is more pronounced for higher turbulence intensities. Haan et al. [15] obtained however that the effect of large integral scales up to $L/c = 7.8$ is still remarkable.

On the wake of the results for bluff bodies, a limited amount of research has been conducted also on the evaluation of the effects of inlet turbulence on typical WT blades [16]. In particular, the stall mechanism is sensitive to turbulence intensities at the inlet, for various Reynolds number regimes [17]. However, it is not clear, whether this is associated will small or large integral length scales. Nevertheless, a twofold effect is noticeable on aerofoils: (i) the triggering of laminar-to-turbulent transition of the boundary layer (decreasing maximum Lift); (ii) the increase of transport of momentum between the boundary layer region and the undisturbed flow, thus increasing the resistance against adverse pressure gradient and delaying separation (increasing maximum Lift). Although the second effect is more pronounced [18], the presence or lack of transition must be carefully accounted [9].

It appears that an increase in turbulence intensity enhances WT blade properties, causing a delay in stall and an increase in maximum Lift and aerodynamic performance [10], [19], [20]. Maldonado et al. [9] add that large scales dampen the actual effect of turbulence, but the limited range of turbulent characteristics tested needs further extension to draw definitive conclusions on this issue.

This work will present the first results of an experimental investigation, which tries to go beyond limitations in the experimental setup, testing a wide range of turbulence scales and intensities and correlating them with the angle of attack and the stall mechanism. University of Liége. The aim of the experiment is to understand the role of the length scale of turbulence in influencing the aerodynamic performance of wind turbine aerofoils.

METHODOLOGY

The aerodynamic behaviour of a Wind Turbine aerofoil is tested in the wind tunnel of the University of Liége. The parameters which govern the behaviour are basically the variation of the angle of attack α and the Reynolds numbers Re_c. In this experiment, the further parameters of the turbulence intensity $I = \sigma_u/\bar{u}$ and the integral length scale L are studied, with particular reference to the pressure distribution along the aerofoil.

The experiment will be fulfilled at the University of Liége. The setup is outlined in Fig. 1.

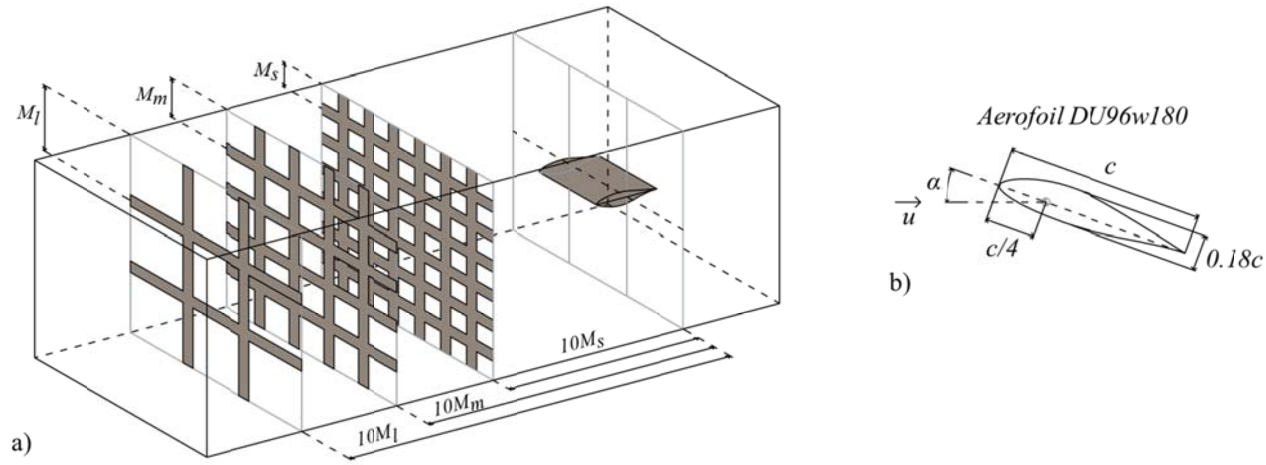

Fig. 1 a) Wind Tunnel Experimental Setup, with the set of three grids; b) the aerofoil model.

The wind tunnel of the University of Liège is a closed loop subsonic boundary layer wind tunnel (*Mach<0.15*), with the possibility of an open-loop configuration. The test-section of *1.80×2.00×2.50m* is placed at *16.00m* from the inlet nozzle. This distance is suitable for the development of a wide range of turbulent inlet structures, which will be generated using the passive grid technique. The generation of vorticity due to the presence of the grid and the consequent drop in the pressure field cause the quiescent upstream flow to develop isotropic turbulent characteristics, which is ideal in order to understand the role of simple turbulence statistics. Various typologies of grids are reported in the literature. However, the square barred grid is accounted as the most reliable geometry of generating an isotropic uniform turbulent flow-field [21].

A set of passive grids, consisting of a mesh of square wooden bars, will be implemented. Various turbulence structures will be obtained by varying bar width d and mesh pace M. The distance x upstream to the model is a parameter to be controlled. In order to have isotropy, a distance of at least $10M=x$ has to be kept.

A preliminary grid setup is proposed in Tab 1.

Table 1. Proposed setup of the set of grids.

Grid	Bar Size		Mesh Size		Min. distance		Porosity
	d [m]	d/c	M [m]	M/c	$10M=x$ [m]	x/c	$\beta=(1-d/M)^2>0.5$
Small, *s*	0.025	0.2	0.125	1	1.25	10	0.64
Medium, *m*	0.0625	0.5	0.375	3	3.75	30	0.69
Large, *l*	0.1875	1.5	0.75	6	7.50	60	0.56

The wind turbine aerofoil to be tested is the DU 96w180, designed at the University of Delft [22]. Regarding the size of the model, following considerations on the choice of the chord length have been made. The use of a passive grid allows for a length scale of $L_{x,max}\cong 15\text{-}20cm$. In order to test the effect of large scales, a model with a rather small chord length $c\cong 0.1\text{-}0.15m$ is necessary. The literature confirms the difficulty in simulating large scales in wind tunnels and the necessity of a small chord [20]. Therefore, for this experiment, two chord lengths are chosen to be tested with the set of three grids. A first model, $c_1=0.125m$, will allow the performation of surface pressure measurements, while a second model $c_2=0.025m$, will allow the estimation of large scales, measuring the aerodynamic forces on the model. The latter will obviously require a correction of the velocity of the wind tunnel in order to match the Reynolds number which is chosen for the c_1 model. Regarding the Reynolds number, two ranges are chosen in particular: 1) low-Reynolds range $\mathcal{R}e\cong 1.5\times 10^5$; 2) high-Reynolds range $\mathcal{R}e\cong 1.5\times 10^6$. However, the main parameter to be varied throughout the experiment is the angle of attack α (Fig. 1). A large range is proposed, to understand the role of turbulence with specific regard to the stall mechanism: 0) Zero angle *0deg*; 1) Pre-stall *2-8÷10deg*; 2) Stall *10-15deg*; 2) Post-stall *10-20deg*; 3) Full-stall *20-45deg*.

The following table introduces the experimental campaign to be fulfilled, with an estimation of the number of setups.

Table 2. Experimental setup.

Grid M/c_l, d/c_l, β	Position of the grid *x [m]*	exp. turb. Intensity *I*	expected int. length scale *L*	Range of angles α	Estimated experiments
Undisturbed	-	*<0.1%*	-	*0-45→5* conf.	*4-5*
Small (1, 1/5, 0.64)	$x=10M_s=1.25$	*high*	*Small*	*0-45→5* conf.	*16-20*
	$x=10M_m=3.75$	*normal*	*Small*	*0-45→5* conf.	
	$x=10M_l=7.50$	*low*	*Medium/Small*	*0-45→5* conf.	
	$x=5M_s=6.25$	*low*	*Small*	*0-45→5* conf.	
Medium (3, 0.5, 0.69)	$x=10M_s=1.25$	*high*	*Small*	*0-45→5* conf.	*16-20*
	$x=10M_m=3.75$	*high*	*Medium*	*0-45→5* conf.	
	$x=10M_l=7.50$	*low/normal*	*Medium/Large*	*0-45→5* conf.	
	$x=5M_s=6.25$	*normal*	*Medium*	*0-45→5* conf.	
Large (6, 1.5, 0.57)	$x=10M_l=7.50$	*normal*	*Medium*	*0-45→5* conf.	*12-15*
	$x=5M_s=6.25$	*normal/high*	*Medium*	*0-45→5* conf.	
	$x=7M_s=8.75$	*normal/low*	*Large*	*0-45→5* conf.	

The use of two models allows for a wide range of turbulence characteristics to be related and compared. However, such a wide variability of parameters has to take into account the actual content in small scales, as a growth in integral length scale is usually related to a change in the small scales content.

These results will be used as validation for future test-cases on the flow pattern on aerofoils.

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