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Effect of atmospheric turbulence on the aerodynamics of wind turbine blades

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EFFECT OF ATMOSPHERIC TURBULENCE ON THE AERODYNAMICS OF WIND TURBINE BLADES: A REVIEW

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ABSTRACT

As Wind Turbines (WTs) operate in the atmospheric boundary layer, the atmospheric turbulence may have a significant effect on their overall aerodynamic forces distribution. Therefore, the resulting flow pattern varies, and it becomes complex to weight up simultaneous presence of inflow turbulence and other issues, such as unsteadiness, three dimensionality or rotation. Steady wind condition is an off-design condition, but it is habitually used in both design and research. This paper aims to give a review of the research about the effects of turbulent inflow experienced by WT blades. A first introduction to the broad subject of WT aerodynamics is proposed, with particular reference to the stall mechanism that is recognized as the leading phenomenon for the comprehension of turbulent effects on the flow pattern, as separation point position, critical angle of attack and the onset itself vary strongly with level of atmospheric turbulence. A brief introduction to the nature of turbulence found within the urban environment further clarifies the major role of inflow unsteadiness, as many attempts are currently made to enhance Urban Wind Energy. A review of state-of-the-art research is then given, in order to underline current limits of research, highlighting eventual role of possible concomitant issues, such as rotation or rotor yaw angle. In particular a critical review of the used turbulence intensities and length scales is given, for their variation strongly affects significance of experiments and simulation. To fulfil this purpose a quick summary to the methodology, especially to Computational Fluid Dynamics analysis, is convenient, with special reference to possible ways of generating artificial inlet turbulent flow field. It has turned out that a "back to basics" approach is needed in order to provide thorough understanding of the effect of turbulence on the stall mechanism and the aerodynamics of the wind turbine, to overcome actual gaps in research.

INTRODUCTION

Annual wind power installations in the European Union (EU) have increased steadily from 3.2 GW of overall power capacity in 2000, to 11.8 GW in 2014, being nowadays the fourth source of power production, with its nearly 15% of share [1]. To withstand the challenge of producing ever less costing energy, wind turbines (WT) have grown up considerably, becoming the biggest rotating machines operating on earth's surface (up to 164-171 m rotor diameter and 8-7 MW power yield respectively by Vestas and Samsung [2]). Since they are placed in the lowest part of the atmospheric boundary layer, they are exposed to highly unsteady inflow conditions and lower velocities. Hence WT aerodynamics has developed into an autonomous subject, since many issues are not encountered in classical aeronautics [3]–[5].

The atmospheric boundary layer (ABL) is the part of troposphere where the effects of the surface of the earth are detectable. This includes large fluctuations in the velocity components, and a shear stress [6]. The harvesting of wind energy for producing electricity involves two processes: the conversion of flow kinetic energy into mechanical torque and then the mechanical torque into electrical power. The performance of both processes show a strong dependence on wind velocity fluctuation. Furthermore, WTs are usually placed in arrays or clusters, their inflow being disturbed by the wake of upcoming WTs. This arrangement makes the aerodynamics

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of WTs even more complex. Literature about WT arrays focuses on the way the wake can be modelled, with reference to WT typology and the position of the rotor [7], without taking directly into consideration the WT characteristics.

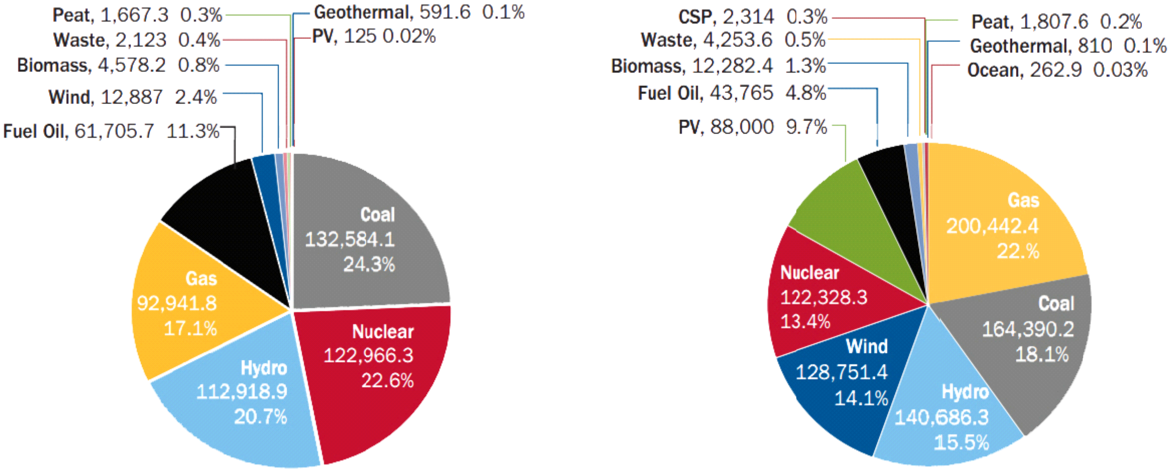

Figure 1. Distribution of European power production, in MW, by source in 2000 and 2014 [1].

Currently, steady wind is the off-design condition. However, it is normally accepted by designers to consider steady data to be then adapted for actual design purposes [8]. In fact, numerous phenomena, which will be discussed later in more detail, contribute to unsteady wind inflow. However, their role is neither completely distinguished nor weighted up, but it strongly affects the behaviour of a WT [9].

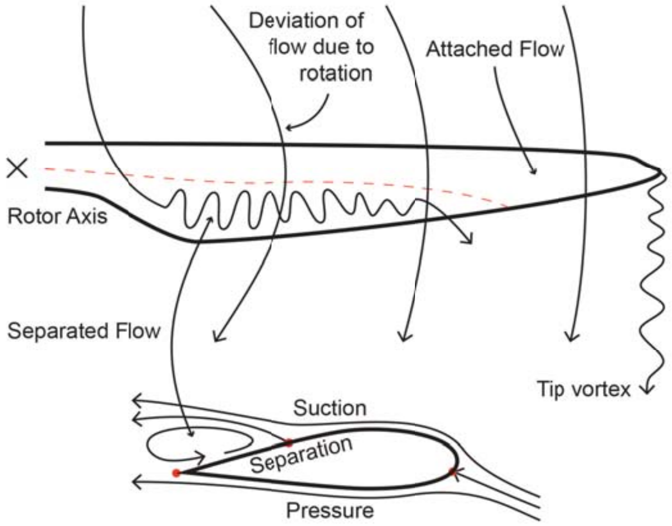

Figure 2. Flow pattern over a WT blade, showing the separation area on the suction (upper) side of a Wind Turbine blade, and the centrifugal deviation of attached flow due to rotation.

In order to gain better understanding of unsteadiness of the atmospheric wind on the aerodynamics of WTs, the complex and unsteady flow pattern over WT blades should be considered in further studies. In particular, the following aspects have been highlighted in the past research:

- Yawed flow, i.e. the azimuthal misalignment between the rotor axis and the wind direction [10];
- Tower shadow, i.e. the dynamical phenomenon, which occur on the blades when they get through the tower during rotation;
- Flow interferences with upstream WT's wake, i.e. particular flow patterns in aligned wind turbines;
- Rotational augmentation;
- Root, tip and 3D effects;
- Roughness of blades, in particular of the leading edge, due to debris or insects or micro-dents;
- Aerofoil geometry and blade planform;
- Atmospheric Boundary Layer properties, such as wind shear over the rotor, i.e. the vertical gradient of wind velocity distribution, the fluctuations in velocity, or rather turbulent intensity and length scale, intermittent wind, such as gusts or extreme events.

These topics represent current active research in the aerodynamics of WTs [8], [11], [12].

Unsteady phenomena have also a great impact on the control strategies. Nowadays active full-span pitch control is the standard method in the control system of WTs. However, there are some drawbacks in this method, i.e. reliability of the pitch actuation system and higher cost, but the latter is offset by saving on the blade construction. For small and medium WTs, the pitch angle is modified for the blades altogether, accordingly with free-stream wind velocity. For large WTs, more advanced systems are under development, like the individual pitch control, IPC. This way, the heavy differences in the loading of the single blades due to wind shear and the differences in wind fluctuations at the top and the bottom of the rotor, are weakened [4]. To achieve this compensation of asymmetrical loading, multiple measures of local turbulence statistical quantities are needed, since asymmetrical loading is essentially dominated by the variation of turbulence intensity and length scale within the rotor area. It is thus believed that better understanding on the flow pattern over WT blades is essential for these machines to grow further in size [13].

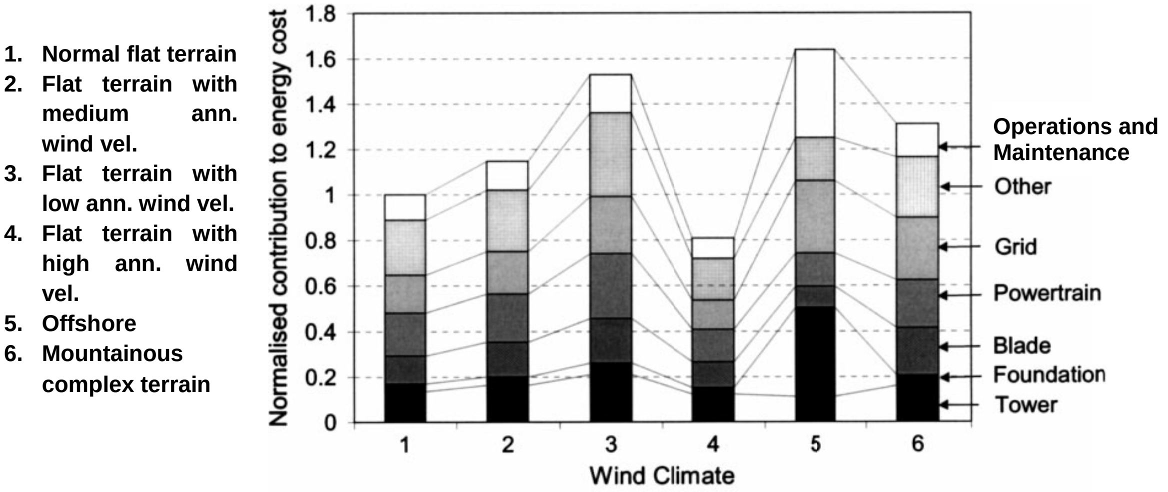

Figure 3. Cost distribution for WTs referred to different wind climates. Reproduced with permission from [14].

Another issue that is gaining growing importance and concern is the optimal choice of a WT typology for a given site. The design optimization can lead to an overall reduction of costs up to 15%, though the choice of high wind speed sites remain favourable in lowering energy costs. Therefore, proper modelling of the actual climate of a WT site, with its turbulence characteristics, is likely to become the future standard in WTs farms design procedures [14]. It is also interesting that the larger percentage of the cost of a WT is provided by its structure, i.e. tower and foundations, and the rotor, showing that properly assessment of aerodynamic loading may lead to significant developments.

This paper focuses on the effects of inflow turbulence, with special reference to the flow pattern over the WT blades. An overview of the physical effects of inflow turbulence is given in the first Section, which namely pertain to the stall mechanism. A general review of literature of stall mechanism is given in the second Section. A brief introduction is also provided to the experimental and numerical methodologies, which have been used, or can be used in the investigation of stall mechanism under varying turbulent inflow. A brief description of the ongoing research within the European project “Aeolus4Future” will conclude the discussion, giving some sparks for further investigations or connections with other topics.

OVERVIEW

As introduced, inflow turbulence normally found within the ABL, causes significant effects in the aerodynamics of WT blades. This particularly applies to their flow pattern behaviour. Before giving an in-depth review of the literature in the effects of atmospheric turbulence on wind turbine blades, firstly a definition of atmospheric turbulence and secondly an introduction on the resulting physics of the flow pattern over the blades are given in this Section.

The lowest 1-2 km layer of the troposphere consists typically of highly turbulent flow. This is because of the vertical exchange of momentum, heat and humidity between the surface of earth and the lower part of the atmospheric boundary layer, ABL. This applies both to night and daytime, and if the wind velocity is high, the ABL is fully turbulent, and its depth becomes highly dependent on wind characteristics. An important issue for the ABL is stability. The depth of the so-called mixing depth, which is the height of the ABL, may vary from several km in the daytime (unstable conditions) to few hundreds of meters during the night (stable conditions) [15]. By neglecting the effects of surface temperature and heat transfer within the ABL, then the so-called neutral conditions are found. Neutral ABL represents the classical wind assumptions. Full-scale measurements have confirmed that neutral conditions represent less than the 30% of the total lifetime of a WT [16]. Turbulence is then enhanced for most of the operating conditions of a WT. The ABL can be divided in sub-layers, in particular the surface layer, SL, sometimes constant-stress layer, for its properties, and the Prandtl layer, PL [17]. WTs traditionally have to deal with the SL, but the growth in dimensions together with stable conditions, i.e. operation by night, gives also the PL a role. This yields an important wind shear over the rotor area and high values of turbulent intensity, TI, together with a large spectrum of turbulent length scales, TLS [15].

The atmospheric turbulence over flat terrains, hills and sea-surface has been for a long time investigated, hence we refer to the existing literature on the topic [6].

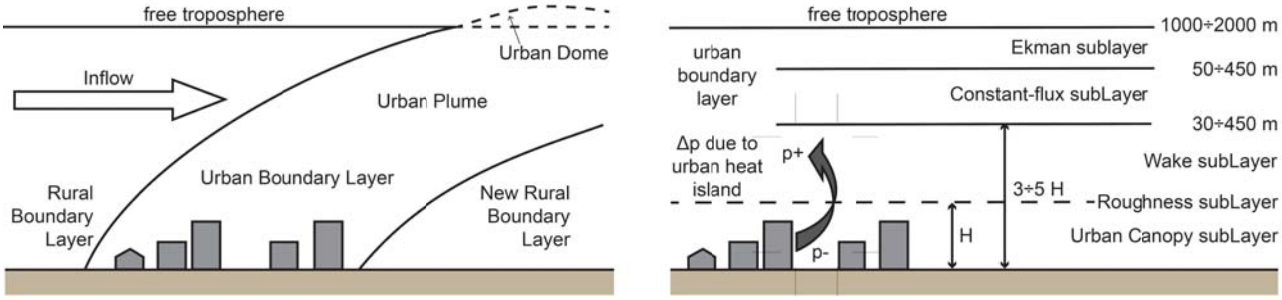

Figure 4. Urban plume downwind a large urban settlement and the vertical layers of the UBL.

Urban environment represents a new interesting topic in ABL studies. Since urban settlements are in constant growth, an alternative to the high costs in transportation of the energy from the primary source to the users may be the placement of a WT in an urban area, or rather within the so-called Urban Boundary Layer, UBL. The flow in UBL features a particular meteorology. This occurs both for the additional roughness provided by buildings and the so-called Urban Heat Island. In effect a secondary circulation of the wind towards the city centre exists due to local high temperatures due to heat sources and stagnant flow radiated areas. Referred to the ABL, the UBL may be interpreted as a sub-layer, called urban plum, but this definition is misleading, because the height of the UBL is usually higher than that of the ABL [18], [19].

The main aspect of UBL regards large roughness elements, sealed areas, reduced permeability of surface and heat storage, that is enhanced turbulence intensity and strong heat fluxes. A greater depth of the boundary layer is recognisable, the so-called Urban Dome, where a stable nocturnal boundary layer is prevented [20], [21]. According to recent studies [19], [22], the UBL can be divided into four layers:

- the urban canopy layer, UCL, up to mean top of buildings;
- the wake layer, 3 to 5 times the mean building height;
- the constant flux layer or inertial sub-layer, which is akin to the Prandtl layer;
- and the Ekman layer, where the wind direction adapts to the geostrophic winds.

As expectable UBL wind and turbulence have different features compared to those of flat terrains. However, a better understanding both of the turbulence within the UBL and a realistic representation of the flow field within street canyons and on top of building is still needed for Urban Wind Energy to take place. Typical features of the UBL are a higher wind shear, doubled turbulence intensities and a nocturnal increase of the fluctuating component of wind speed with height. However one must pay careful attention to the actual wind profile: for large WTs simplified profiles may be used, while for Small Wind Turbines placed in the urban canopy layer an improved approach is needed, in order to properly evaluate the local effects provided by isolated buildings or particular features of the heat and humidity flux [13], [23]. The wind flow in the sub-canopy layer is strongly influenced by buildings, which experience massive flow separation-reattachment where eventually Small WT could be placed. The location of such devices in order to maximize energy is hence not clear, since the circulation and shear regions due to local bluff body aerodynamics have an extremely broad variation from case to case [24], [25]. Furthermore, the effects of the UBL can be recognized also within several km of distance from the city centre, which gives further hints regarding necessary studies for the siting of wind turbine arrays and clusters [26]. This suggests several possible studies, such as the modelling of the wake of the impact of urban wakes within the surrounding environment, especially suitable for coastal cities with possible siting for offshore wind power plants, or also the implementation of a database of turbulence data with respect to different urban typology and wind profiles. Also the role of atmospheric stability is still to be fully defined. The Richardson number $\mathcal{Ri}$ is a valuable parameter to be correlated with a reference WT's response in order to assess these effects [16].

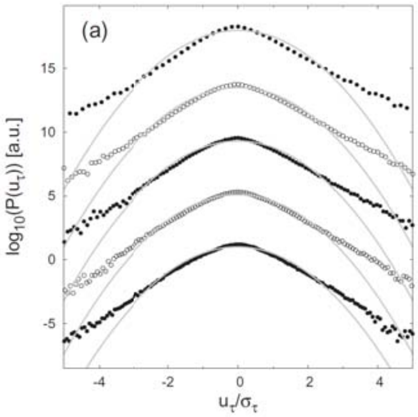

Figure 5. Characteristic spectrum of wind speed fluctuation found within the atmospheric boundary layer, with "fat tails" and non-Gaussian distribution. Reproduced with permission from [27].

Once the turbulent wind has formed, it encounters a wind turbine, an isolated one, or an in array. This acts from the WT's point of view as an inlet condition, i.e. unsteady turbulent inflow for the WT blades, which are the interface between the rotor and the wind field. WT blades experience an almost unexplored field of aerodynamics: the unsteady separation-reattachment flows under a specific Reynolds number, depending on the wind speed and size of the WT. This occurs because the research on unsteady flow over aerofoils, i.e. the cross-section of a blade, has been conducted primarily for aeronautical applications, which tend to avoid high and moderate turbulence levels and have high Reynolds numbers and very thin aerofoils. The turbulence level on the far thicker wind aerofoils varies from 5% of offshore to 25% on on-shore [28], and even more for Urban Wind Energy [15]. The integral scale of turbulence has also a major impact on the overall aerodynamic performance. It varies from 0.001 m to almost 500 m [29], but a classification can be done if referred to the chord-length. If the length scale is comparable with the chord-length, the classical statistical theory is valid, and the inflow conditions can be considered steady. If the length scale is comparable to the rotor diameter, or bigger, the inflow can be considered unsteady, because of the great variation of velocity directions, the so-called gusts. The wind velocity becomes intermittent, which yields that classical statistics of wind, as in the spectral gap found by Van der Hoven, are not applicable (fat tails in the Weibull distribution of the wind velocities, with significant role of the skewness and excess kurtosis statistics, [27], [30]).

The inflow turbulence has two effects on the WT blade boundary layer [31]:

- Triggering of laminar-to-turbulent transition of the boundary layer, which lowers resulting lift;
- 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, which means maximum lift increases (Fig. 7).

Before giving a thorough review of the research on this topic, a clarification of the research field regarding flow pattern over an aerofoil is mandatory. Presuming to have uniform inflow, with the variation of the angle of attack, aerofoils experience a broad range of aerodynamic loading. If the angle of attack varies sufficiently slowly, the behaviour experiences a sharp change in correspondence of a certain angle of attack, which is called static stall angle. Usually, this goes along a drop in lift coefficient, but it strongly depends on the geometry. For higher angles of attack stall continues developing until full stall is present. In the literature full stall is sometimes called erroneously deep stall.

If the angle of attack varies faster, flow pattern over aerofoils completely changes as it experiences dynamic stall. In aeronautical literature, it is often called deep stall. Deep stall condition has been given a dramatic attention in the last research, since it has been noticed important discrepancies in the expected durability of wind turbines and the resulting one. The flow over dynamically stalled WT blades presents a vortices pattern on the suction surface of the aerofoil (dynamic stall and aft dynamic stall vortices, denoted as DSV and ADSV). Since direction of wind and aerofoil are not coupled, deep stall is always present in VAWTs, and it is the main reason of their lower power coefficient [32]. It is also present in HAWT, but in a limited way, even if pitch control is used, for many reasons: dynamic pitching of aerofoils, yawed flow (which is a very common operating condition for WTs in arrays and clusters), wind shear and atmospheric turbulence, wind gusts and extreme events, tower shadow. It was argued that dynamic stall only occurs after static stall angle. In addition to the characteristics of the incoming flow, aerofoil geometry, frequency and amplitude of pitching, provide a strong variation of its behaviour. Though many experiments have been performed [33], they concern mainly helicopters aerodynamics, with the aim of avoiding dynamic stall optimizing aerofoils' shape, while in WT blade aerodynamics it always occurs.

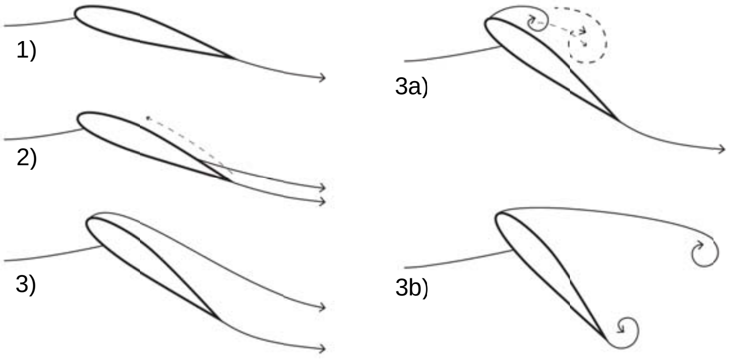

Figure 6. Evolution of stall mechanism with angle of attack α.
1) $\alpha \leq \alpha_{cr}$ the flow is fully attached; 2) Trailing edge separation with separation point moving forward with increasing α; 3) Full stall with separation point on leading edge. In presence of dynamic pitching different flow patterns are experienced.
3a) Dynamic stall Vortex; 3b) Aft Dynamic Stall Vortex [9], [34].

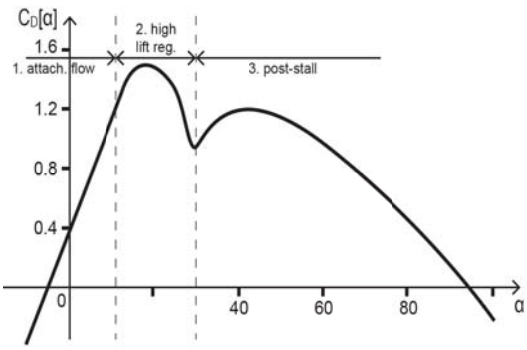

Figure 7. Typical distribution of Lift coefficient for steadily varying angle of attack α. 1) flow is attached; 2) trailing edge separation with steep drop of lift; 3) full stall development with leading edge separation.

Classical aerodynamics refers to the described mechanism as Stall Mechanism. At this point, a remark is useful regarding the limitation of the subject. As pointed out wind turbine aerodynamics is quite a new subject for a number of reasons. An additional one is the scope of the subject. Bluff body aerodynamics studies massive separated-reattached flows over not streamlined, with a flow pattern that experiences most circulation and shear regions all over the surfaces of the body. On the other hand, classical aerodynamics was bound to aeronautical problems, i.e. streamlined bodies, with mainly attached flow with a completely different pattern and method of assessment. WT blades under pitch control are in-between: the flow remains attached for a meaningful part of the time, but for far more time is separated, experiencing static or dynamic stall, whose complex development and dynamics is yet to be fully mastered [4], [35].

Stall is the main feature of the flow to be thoroughly understood, as through it, turbulent inflow strongly affects WT blade behaviour [36]. Stall effects have been detected since the very first wind energy applications. The Danish Concept used stall in order to limit the power coefficient for the highest wind speeds. However, it resulted in higher loading on structural elements and irregular distribution of torque. For this reason, both the tower and the drivetrain/generator complex experienced high vibration rate and, hence, fatigue. This has resulted in premature failures and unexpected shutdowns. The lack of knowledge has brought manufacturers to prefer pitch control systems, instead of stall control [3]. In any case, some attempts are continuously performed in order to improve performance under stall, e.g. the use of vortex generators to improve the overall performance and eliminating the risk of furling at the higher wind speeds [8]. Even though modern WT have improved considerably, the ongoing lack of comprehension of stall onset and development is responsible of expensive controlling systems and still short life-cycle of the overall wind turbine systems [12].

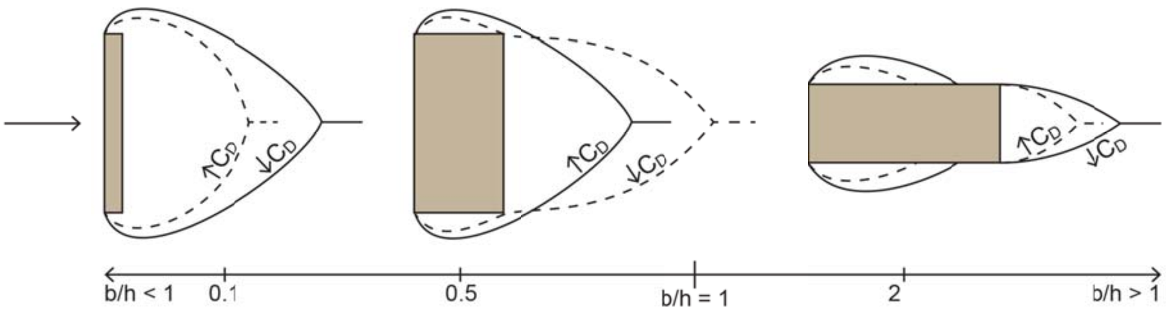

Figure 8. Massive separated flow over a bluff body for smooth flow (solid line) and turbulent flow (dashed line), showing variability of the effect of turbulence with shape aspect ratio [31].

Static stall occurs when separation of flow pattern on the suction (upper) surface of the blade takes place lifting the angle of attack, e.g. pitching the blade. A vortex first detaches from the trailing edge, the separation point moves towards the leading edge until the blade turns fully stalled, and a vortex detaches from the leading edge. If stalled, the blade yields also a turbulent wake, with sudden modification in the aerodynamic efficiency. The effects of stall are well known: the aerodynamic lift coefficient drops, to then recover slowly to a new maximum while the drag coefficient slightly increases steadily [4], but the angles of attack and the rates of decrease/increase are extremely variable from aerofoil-to-aerofoil [37]. In fact, stall depends on many aerodynamic features:

- Aerofoil typology, i.e. the blade cross-section, usually variable span-wise;
- Pitch angle of blade, ϑ, i.e. the geometric inclination of the blade-chord with respect to the plan of rotation. This is the main parameter regarding power control system;
- Angle of attack, α, i.e. the relative angle between the chord line of aerofoil and the apparent direction of flow, which depends basically on the tip speed ratio, λ;
- Blade and leading edge roughness;
- Rotation of blades, i.e. centrifugal and Coriolis effects yielding rotational augmentation;
- Tip and root region highly three-dimensional behaviour;
- Unsteady inflow, i.e. inlet turbulence intensity and diverse length scales of turbulence.

Stall mechanism is yet to be fully understood, in particular the influence of above parameters and their relative weight in modifying power yield has not yet been clarified [38]. Nevertheless inflow turbulence effects are of utmost importance, once geometry and tip-speed ratio have been defined [39].

Stall and its modifications due to turbulence have also an impact in the research on wind turbine wake aerodynamics. This subfield of studies has developed in order to assess the effect of the wake of upstream wind turbines in arrays and clusters occurring in wind farms. In particular, the stall mechanism is strongly responsible of the modifications to the near wake of a WT. Further reference may be found in [7], [40].

Another issue must be raised, regarding the prediction methods used for assessing the actual unsteady load distribution for WTs. The overwhelming majority of WTs are designed following the Blade Element Momentum theory, BEM, which assesses the unsteady aerodynamic loading over the blades, hypothesizing that the annular strips of the rotor are independent one another, hence giving the possibility to use 2D aerofoil data and simplifying the calculations. 2D aerofoil databases have been used in aeronautics since long time, giving reliable and accurate results, but for WT aerodynamics, their reliability is at issue, since they often lack of high angles of attack and unsteady and 3D effects are taken into account using empirical rules. Furthermore such databases do not comprise of varying inflow turbulence, and its effect is usually neglected, pointing out that under neutral conditions aerodynamic loading is higher and turbulence effects are less evident, but the lack in the method and in the research is noticeable [41]. It is out of the scope of the present paper to provide a review of BEM, and then we refer to [8].

DISCUSSION OF STATE-OF-THE-ART

The effects of turbulence on the separation properties of a bluff body are not a novel topic of research. The effects of free-stream turbulence on the separation-reattachment flow for both edged and curved bluff bodies have been experimentally investigated since 1980s. Turbulent shear flows have been investigated thoroughly for backward facing steps, forward facing steps, and blunt plates, in a variety of different configurations. They offer a good prototype for fine-tuning and assessing more complex flow behaviour. The results agree upon turbulence intensity having a strong correlation with the reattachment length, even compared with other parameters, such as roughness [42]. This occurs because, as a rule, turbulence delays the onset of stall and diminishes the dimension of the separation bubble [43], [44]. These simplified studies are very useful to evaluate methods and procedures, which are supposed to be applied in complex engineering problems, such as wind turbine aerodynamics. They have shown a multitude of occurring phenomena, whose weight is yet to be rated [9].

As introduced thoroughly, turbulence effects on WT aerofoils are being an enhanced branch of research, for the need of getting reliable 2D aerofoil data, since nowadays, in spite of some renewal attempts, BEM is still the only used design methodology [8].

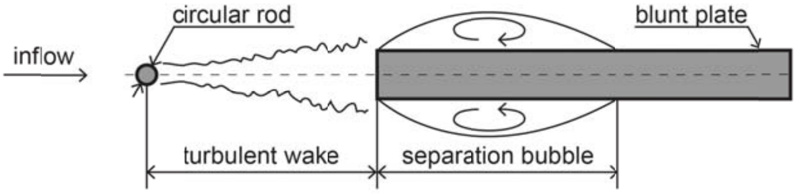

Figure 9. Blunt plate experiment set, with flow configuration, as in [45].

Effects of inflow turbulence on separation flow over aerofoils have been a research topic for a long time [46]. First of all the inner nature of chosen inlet turbulence is questionable, since a wide range of turbulence parameters has been used in research, depending on wind tunnels' setup. In fact, it has been immediately noticed that discrepancies of aerodynamic loading may be present, due to different wind tunnels, at same velocity and Reynolds parameter. The first results showed that turbulence intensity enhances WT blade property, causing a general increase in Lift and aerodynamic performance [4]. Later it has become clear, that this occurs since turbulent intensity raises the level of energy of the boundary layer, i.e. its thickness, causing an adverse pressure gradient to be less effective in trigger separation, causing the stall to delay and the lift to rise [4].

Other factors concurring with inflow turbulence are: the Reynolds number, the roughness of the blade (in particular of the leading edge of the blade) and the tip speed ratio. To weight up the role of turbulence and those other parameters is still a hot topic in research. The shape of aerofoils and the blade planform is optimized towards to enhancement of lift in presence of roughness. Here the $\mathcal{Re}$ numbers, assessed experimentally, are used for comparison with the observed real-scale flow regimes.

Various scales of the WT blade and aspect ratios have been tested (ratio thickness to chord-length, and Reynolds range). To get further understanding of the problem, also flow visualizations have been performed. In the first investigations of the topic [46], [47] an increase of the lift coefficient was noticed, with no rising of the drag coefficient. Also the laminar separation bubble was affected by incoming turbulence, as it disappeared for higher level of TI.

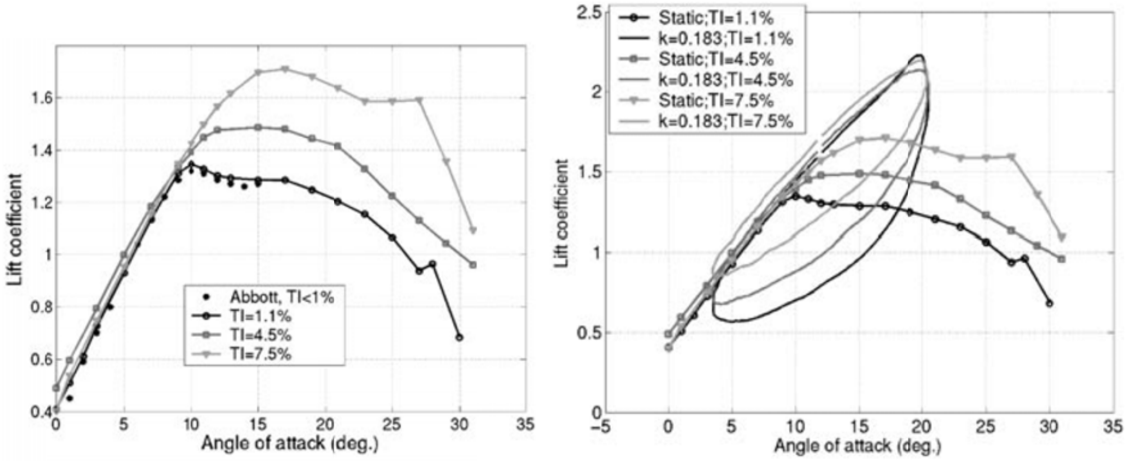

Figure 10. Lift coefficient variation under varying turbulent intensity of inflow, for a) static and b) dynamic (with comparison) condition. Reproduced with permission from [48].

The angle of attack, α, is the governing parameter of the flow pattern and the stall regime of a WT aerofoil, thus it is used as the reference in more recent experiments.

An insight over the properties of an aerofoil with varying angle of attack has been given by [49] for different Reynolds numbers. The delay of stall is present, but the low level of turbulence did not give further understanding of the effective importance of the topic.

A more systematic work is represented by [50], further developed by [39], who respectively studied the steady and the unsteady properties of the separation flow over a pitching aerofoil. Being submerged in the ABL or placed in clusters, WTs experience a broad range of TIs and AAs, which have to be carefully weighted up. The blades experience, as expected, an increase in lift due to turbulence, though with higher levels of turbulence the Reynolds number has a negligible effect. This occurs because of the oscillation of the position of the separation point edge-wise.

The rotational motion of blades also influences stall. This is called rotational augmentation, and its effect is to delay stall due to the combined effect of the Coriolis forces span-wise and centrifugal pumping edge-wise [51], but its physical mechanism is yet under argument [52]. Nevertheless, if compared to inflow turbulence, the effects of rotational augmentation on the overall aerodynamic loading seem to be negligible [36].

Both HAWT and VAWT have been tested. But there are some fundamental differences: while for a VAWT the clue is given to the power efficiency, to HAWT the detailed assessment of the aerodynamic unsteady loading is at issue. Nevertheless, the power coefficient depends essentially on the Reynolds number and on the mean wind speed, while structural issues are rather more important.

Usually the increase in lift caused by turbulent intensity goes along an increase of drag, but this varies strongly with the typology of aerofoil. A comprehensive evaluation of the stall mechanism development with regards of the free-stream turbulence should also consider the role of not only the turbulence intensity (being careful about the definition of the time-record), but also of length scale and isotropy, which can lead to broad variation in results [53]. Reviewed experiments do not give a physical explanation on the actual role of these parameters, but it is commonly accepted that turbulence intensity gives the flow enough energy to remain attached to the suction surface for longer times, hence enhancing lift and overall aerodynamic performance, if the turbulent length scale is comparable with the chord-length and turbulence is isotropic [41].

Numerical simulations are also under study, showing the complexity of solving the upstream flow turbulence. Nevertheless, they represent a powerful tool for the description of stall mechanism, since one can highlight the importance of effects such as three-dimensionality on the overall power performance [32], [54].

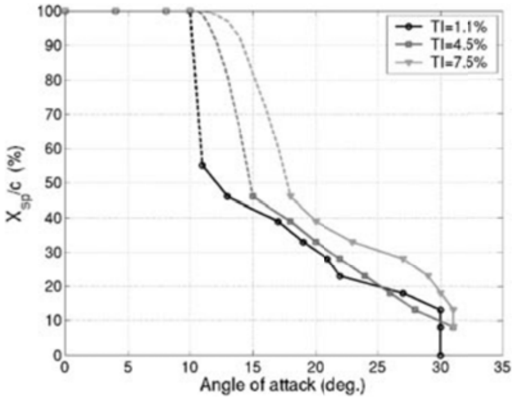

Figure 11. Influence of the turbulence intensity on the location of the separation point as a function of the angle of attack. Reproduced with permission from [48].

Only one work so far, to the knowledge of the authors, has come up with an assessment of deep stall mechanism under varying inflow conditions [48].

A critical evaluation of presented works suggests following weaknesses in the research:

- Role of turbulent isotropy and comparison with actual atmospheric turbulence characteristics (isotropy of turbulence is not a natural condition of wind flow, but it is the only studied condition in wind tunnels);
- Role of intermittent statistics of wind on overall structural reliance and power efficiency, i.e. due to larger length scales or gusts;
- Study of turbulent effects based on their length scales (usually wind tunnel experiments present length scale which is comparable to chord length, while in the ABL usually bigger scales are found);
- Study of reduced frequency and tip speed ratio variation occurring for fluctuation in wind velocity, i.e. the asynchronous response of a structure under intermittent loading (fatigue issues);
- Study of coupling effect of rotation effects and turbulent inflow, i.e. rotational augmentation under varying inflow conditions (it is normally accepted for helicopter to consider the rotation as not having effects on stall mechanism, but a coupled evaluation seems to miss);
- Study of three-dimensional effects and two-dimensional data (BEM theory for the design of aerofoil) in order to assess precise power output efficiency and structural reliability;
- Comparison between simulation models (many research are based on RANS and turbulence models in an attempt to validate their applicability to specific problems. For wind turbines, an achievement is missing. It is not clear, whether it is necessary to model the whole turbine with rotating meshes, or to predict actual separation points without laminar-to-turbulent transition models, or further to consider the effect of aero-elasticity of blades in the flow-field, with the implementation of FSI algorithms).

An issue was raised about the proper turbulent statistics to be considered [55]. A correlation between the statistical properties of the turbulence and the transient response of the WT, whether power yield or structural, is strongly dependent on the chosen duration of record, which is often set in 10-minutes time records, due to stationarity hypothesis applicability (spectral gap of Van der Hoven Spectrum) [16]. However, within this particular time record, diverse turbulent structures exist, which play a role in the transient response of the WT [21].

Much more research has been dedicated to the effects of free-stream turbulence in the aerodynamic wake of WTs, since it influences the power coefficient in WT arrays and clusters. Few studies focus on the turbulent inflow conditions, which cause strong meandering of wake and, generally, its quicker decay [26]. However, turbulence induced wake modifications are connectable with stall mechanism detection, thus aerodynamic loads are measured together with velocity deficit in the wake of WTs [20]. Nevertheless numerical modelling of wake aerodynamics has been brought toward a straightforward development, and good results are obtainable. It is arguable that shortly those methodologies may be used for actual site optimization of wind turbine and environmental impact evaluations [56].

This topic is having increasing popularity in the research community, and many research groups are performing investigation on turbulent inflow simulation, wind turbine blade flow pattern under varying inflow and WT response under unsteady aerodynamic loading [34].

METHODOLOGY

To get further insight in assessing the variation of the aerodynamics of a WT blade under diverse inflow conditions, it is useful to provide a brief panorama of the methodologies, which have been used to assess the actual distribution of pressure.

There are essentially three techniques: full-scale measurements, experimental testing and computational simulation.

There are several attempts in the literature to get valuable results from a full-scale wind turbine, whether placed in a real wind farm, or built for this purpose [53]. In particular, even with high resolution measurements of both wind speed and energy output, the results are difficult to generalize. Turbulent gusts affect wind alignment, aerofoil performance and furling limit, which is a major issue especially for small WT, which usually are used in such tests. The impact of turbulence on power output may become less consistent than other issues, such as cutting off and furling effects. This occurs because free-stream turbulence at high speed, near cut-off, causes gusts. Small WTs usually experience intermittent furling with consequently significant hunting and off-axis orientation, with reduction of power generation, which are difficult to relate directly with wind velocity free-stream turbulence. Nevertheless turbulent wind occurs under non-neutral atmospheric conditions for over 60% of the service life [16]. This gives that turbulent structures may need specific statistics of wind, depending on their own extremely variable distribution, which needs to take into account of stability effects. A possible way could be the use of the Richardson number, $\mathcal{Ri}$, definition, in order to get an insight in the correlation of the fluctuating component of wind with dynamic loading. Improved description of atmospheric turbulence is hence needed, which take into account the highly intermittent nature of wind [57].

Wind tunnel testing has been, and still remains, the fundamental investigation mean used in wind engineering for getting further insight on bluff aerodynamics issues. WT aerodynamics is not an exception, and many described experiments focus on assessing the effects of inflow turbulence over whole WTs or WT blades or aerofoils, with or without concurrent phenomena. However the way inflow turbulence is created, strongly affects results [58]. Though it is necessary to reproduce actual site conditions, usually turbulence passive or active grids are used, which produce homogeneous isotropic turbulence that rather poorly represents atmospheric conditions. Furthermore a significant effort has been put over turbulence intensity modelling, without taking care of turbulent length scales, which perhaps have far more important effects on the aerodynamic response of a WT blade [54].

A promising method for getting insight in the actual aerodynamics of WTs is Computational Fluid-Dynamics, CFD, simulation of the problem. While CFD has been representing a very important branch in the subject of wake aerodynamics, there are only few applications concerning inflow turbulence. This is mainly because of the intrinsic difficulty in modelling likely boundary conditions, such as body forces. In aerodynamics, boundary conditions can significantly affect the reliability of results. While for a laminar inflow defining a velocity profile gives an inlet definition, for turbulent inflow, it is necessary to describe somehow the fluctuating component of inlet velocity. Atmospheric turbulence modelling strongly depends on the proper definition of inflow turbulence. A smattering introduction of this important aspect of CFD simulation of turbulent inflow is given, in order to get a smattering introduction of this subject in ongoing development.

First, one should decide whether model the inflow instead of develop it with adding sufficient upstream region to make a laminar input become fully turbulent. The costs of this developing distance are impractical, excepting some particular geometry that presents turbulence depending strictly on some disturbance elements, which can be easily modelled.

Concerning turbulent inflow models, two categories exist:

- recycle/rescale method
- synthetic approach

The recycle-rescale method provides an inlet from computed data from a specific region downwards the simulation or an auxiliary simulation. Three methods are comprised in this category: periodic boundary conditions, PBC, pre-computed method and internal mapping method. The PBC method re-uses outlet data as inlet condition, and it is very useful for a repeated geometry. The precomputed method uses an external further mesh in order to develop desired level of turbulence to then be applied as inlet in the actual simulation. The internal mapping consists of the collection of flow data from a point downwards to be applied as inlet. The latter solution is the most evolved, but it introduces an error that can be controlled by imposing the divergence-free condition.

The synthetic approach is a more refined method that is based on the calculation of artificial fluctuations on the statistical properties, which are imposed to the actual computational domain. They are free from the disadvantages of the recycling methods, the introduction of periodicity of fluctuation and overall error, because a random signal is generated. Several recent studies focus on this method, pointing out that a physical meaning free random turbulence generation is equivalent to a white noise, hence having no tangible difference with the laminar inflow and decaying very rapidly [54]. A coherent structure of the flow is necessary, and the last proposed method focus on its modelling. To impose spatial and temporal correlation two approaches exist: the spectral method and the algebraic method.

Once the boundary conditions are set, one must argue which simulation method is suitable in detecting both the effects on the aerofoil boundary layer and its wake. A very quick introduction to actual state-of-art is given:

- URANS. By averaging the Navier-Stokes equations is it only possible to model the turbulence by computing the eddy viscosity, hence solving only the largest turbulent scales. So far, it has been heavily implemented in all aerodynamics applications, for its computational cheapness. However, even introducing more accurate turbulence models, a validation is always needed since results are often unclear [59].
- LES. The largest energy carrying scales are fully resolved, while the smallest scales are modelled through filtering of the Navier-Stokes. It has become recently more popular, due to availability of bigger computing resources, without having the concern of the reliability of the turbulence model for that specific CFD problem.
- DES. It is a hybrid of RANS and LES, which consists of running RANS in boundary layer and LES in the separated regions for the largest scales. This model has shown issues regarding the quick decay of turbulence, but it is a cheaper alternative to most expensive LES and provides the possibility to introduce laminar-to-turbulent transition models.
- DNS. All range of wave number is solved, giving as drawback the extremely expensive computational demand. Only few applications are effective, but it is considered reliable, as it solves numerically the N-S equations.

Since the number of length scales involved is Reynolds number dependant, one may consider different options, being aware of hypotheses and risks, to save computational effort in order to get optimized, but accurate, results.

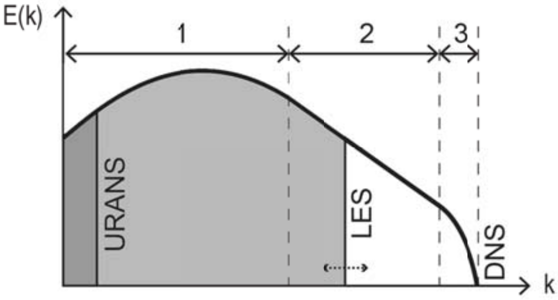

Figure 12. Log-log diagram of the Energy spectrum $E(k)$ of turbulent length waves, k, with indication of its three domains: 1. Largest eddies, where energy is introduced in the flow; 2. Inertial subrange; 3. Smallest eddies, with dissipation into heat. CFD methodology, i.e. URANS, LES and DNS, as referred to solved and modelled turbulent length scales, is shown.

A further aspect, which may be of fundamental importance, is the laminar-to-turbulent transition. It has been found that it can extremely influence results on a boundary layer with detachment and reattachment of flow, such as aerofoil experience. The transitional models are based upon the finding of the critical momentum thickness Reynolds number and the transitional length factor. This subject represents an ongoing research field, even if one can argue this does not apply to WTs. In fact, they are placed in the countryside, and their blades experience high levels of additional roughness (coming up from debris or insects [60]) over the leading edge, which can suggest further research on the presence of an effective laminar boundary layer is possible. In addition, turbulent inflow triggers transition to turbulent boundary layer, suggesting its effect may be of greater importance regarding stall mechanism, than transition. Nevertheless computations and experiments must be in concordance regarding transition assumptions, but sometimes an indication is missing [61].

For the actual state of the art of the computational means, which have shown good results, a thorough review can be found in [62], [63].

ONGOING RESEARCH

To further enhance the performance of wind energy harvesting, the European Union and the member states are investing for research, in order to lower CO_2 emissions by 20% by 2020 (Horizon 2020 ITNs). In particular, this literature review has given some cause for reflection on the topic of the actual inlet flow, which is sensible regarding the evaluation of the operating conditions of a WT in order to maximize its durability.

Within the project “AEOULUS4FUTURE” the Work Package 5 aims to determine the possibility of further exploitation of the urban environment to harvest wind energy. Hence a critical evaluation of the flow in urban environment together with the systematic assessment of effects of higher turbulence and intermittent wind on WT blades is useful for the achievement of introduced aim.

A first assessment of the deviation of theoretical behaviour under different inflow conditions will be performed for a simple model, such as a blunt plate under varying inflow conditions [44], in order to measure the varying length of reattachment and to fine-tune the computational instrument, to then be applied to an existing experiment on a WT aerofoil [41].

A second step would be the a thorough experimental evaluation of the turbulence characteristics found within the urban environment or near coastal areas, with special reference to the integral length scale of inflow turbulence, which causes high turbulent intensities or intermittent wind.

The methodology within this project will be based both on Computational and experimental means, but the final purpose is to add a contribution to the growing field of Computational Wind Engineering, which nowadays enables the extensive use of numerical simulations to be validated with simple experiments [8], [55].

Once an evaluation of the nature of turbulence and its effects for the aerodynamics of a WT turbine blade have been evaluated, an application of a model wind speed time-history could be useful to assess if the fatigue limit state or aeroelastic issues represent some uncertainties. In particular this can be applied both to near-to-coast off-shore applications (which experiences lower turbulent intensity and higher velocity, giving rise to a wider range of turbulent structures) and to urban environment (greater turbulence intensity and lower velocities).

CONCLUDING REMARKS

From the critical review of literature, a “back to basics” approach seems an appropriate technique to assess the effective weight of turbulent inflow, for a given configuration. It also helps to understand the physical behaviour of stall mechanism, as numerous issues affect full-scale measurements, making statement of conclusive remarks difficult. The lack of knowledge regarding the actual prediction of power yield and structural behaviour depends essentially on the Wind Turbine Blade Aerodynamics. The role of inflow turbulence parameters becomes important, yet their effective role has to be understood [7], [64]. An interesting gap in research to be filled is the effective role of the turbulent length scale of turbulence on the flow pattern over WT blades. Other issues are, but not limit to, the role of turbulence isotropy, the statistical representation of intermittent wind velocity, the coupled effects of inflow and rotation or the three-dimensionality of blade [7], [60], [64]. In addition, the effect of laminar-to-turbulent transition upon the overall aerodynamics (usually avoided due to roughness), or the fluid-structure interaction for large WT structures, has to be carefully evaluated. Gaining further insight of turbulent length scales effects may lead to interesting breakthroughs in the implementation of CFD in the design of WT. Actually, the extrapolation of aerofoil data with the effective role of concurring unsteady phenomena, may be enhanced in diffused design methods, such as BEM applications.

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REFERENCES

[1] “EWEA Annual Statistics 2014.” Available: http://www.ewea.org/.
[2] Available: http://www.windpowermonthly.com/.
[3] E. Hau, *Wind turbines: Fundamentals, technologies, application, economics*, 3rd ed. Berlin Heidelberg, 2013.
[4] T. Burton, D. Sharpe, N. Jenkins, and E. Bossanyi, *Wind Energy Handbook*. New York: John Wiley & Sons, Ltd, 2011.
[5] R. Gasch and J. Twele, *Wind Power Plants: Fundamentals, Design, Construction and Operation*, 2nd ed. Berlin, Heidelberg: Springer-Verlag, 2012.
[6] R. B. Stull, *An Introduction to Boundary Layer Meteorology*, vol. 13. 1988.
[7] L. J. Vermeer, J. N. Sørensen, and A. Crespo, “Wind turbine wake aerodynamics,” *Prog. Aerosp. Sci.*, vol. 39, no. 6–7, pp. 467–510, 2003.
[8] M. O. L. Hansen and H. Aagaard Madsen, “Review Paper on Wind Turbine Aerodynamics,” *J. Fluids Eng.*, vol. 133, no. 11, p. 114001, 2011.
[9] J. G. Leishman, “Challenges in Modeling the Unsteady Aerodynamics of Wind Turbines,” *21st ASME*

Wind Energy Symp. 40th AIAA Aerosp. Sci. Meet., pp. 1–28, 2002.

[10] J. Morote, “Angle of attack distribution on wind turbines in yawed flow,” *Wind Energy*, p. n/a–n/a, Jun. 2015.

[11] H. Snel, “Review of aerodynamics for wind turbines,” *Wind Energy*, vol. 6, no. 3, pp. 203–211, 2003.

[12] F. Rasmussen, M. H. Hansen, K. Thomsen, T. J. Larsen, F. Bertagnolio, J. Johansen, H. A. Madsen, C. Bak, and A. M. Hansen, “Present status of aeroelasticity of wind turbines,” *Wind Energy*, vol. 6, pp. 213–228, 2003.

[13] C. C. Baniotopoulos, C. Borri, and T. Stathopoulos, “Environmental Wind Engineering and Design of Wind Energy Structures,” *Springer-Verlag*, vol. 531. Springer-Verlag, Wien, p. 352, 2011.

[14] P. Fuglsang, C. Bak, J. G. Schepers, B. Bulder, T. T. Cockerill, P. Claiden, a. Olesen, and R. van Rossen, “Site-specific Design Optimization of Wind Turbines,” *Wind Energy*, vol. 5, no. 4, pp. 261–279, 2002.

[15] S. Emeis, *Wind Energy Meteorology. Atmospheric Physics for Wind Power Generation*. Berlin, Heidelberg: Springer-Verlag, 2013.

[16] M. M. Hand, N. D. Kelley, and M. J. Balas, “Identification of Wind Turbine Response to Turbulence Inflow Structures,” in *4th ASME/JSME Joint Fluids Engineering Conference*, 2003, no. June 6–10, p. 13.

[17] H. A. Panofsky and J. A. Dutton, *Atmospheric turbulence: models and methods for engineering applications*. Wiley-Interscience, 1984.

[18] B. W. Atkinson, “Numerical modelling of urban heat-island intensity,” *Boundary-Layer Meteorol.*, vol. 109, no. 3, pp. 285–310, 2003.

[19] M. Roth, “Review of atmospheric turbulence over cities,” *Q. J. R. Meteorol. Soc.*, vol. 126, pp. 941–990, 2000.

[20] M. Kanda, “Progress in Urban Meteorology :A Review,” *J. Meteorol. Soc. Japan*, vol. 85B, pp. 363–383, 2007.

[21] J. Hidalgo, V. Masson, A. Baklanov, G. Pigeon, and L. Gimeno, “Advances in urban climate modeling,” *Ann. N. Y. Acad. Sci.*, vol. 1146, no. 2008, pp. 354–374, 2008.

[22] M. Piringer, S. Joffre, A. Baklanov, A. Christen, M. Deserti, K. De Ridder, S. Emeis, P. Mestayer, M. Tombrou, D. Middleton, K. Baumann-Stanzer, A. Dandou, A. Karppinen, and J. Burzynski, “The surface energy balance and the mixing height in urban areas - Activities and recommendations of COST-Action 715,” *Boundary-Layer Meteorol.*, vol. 124, no. 1, pp. 3–24, 2007.

[23] S. Miao, P. Li, and X. Wang, “Building morphological characteristics and their effect on the wind in Beijing,” *Adv. Atmos. Sci.*, vol. 26, no. 6, pp. 1115–1124, 2009.

[24] H. Hemida, A. Šarkic, S. Gillmeier, and R. Höffer, “Experimental investigation of wind flow above the roof of high-rise building,” in *WINERCOST Workshop “Trends and Challenges for Wind Energy Harvesting,”* 2014, pp. p.25–34.

[25] H. Hemida, A. Šarkic, and R. Höffer, “Interference effect of high-rise buildings for wind energy extraction; wind tunnel and numerical investigations,” in *14th International conference on wind engineering*.

[26] M. B. Christiansen and C. B. Hasager, “Wake effects of large offshore wind farms identified from satellite SAR,” *Remote Sens. Environ.*, vol. 98, no. 2–3, pp. 251–268, 2005.

[27] T. Mücke, D. Kleinhans, and J. Peinke, “Atmospheric turbulence and its influence on the alternating loads on wind turbines,” *Wind Energy*, vol. 14, no. 2, pp. 301–316, 2011.

[28] I. Antoniou, D. Asimakopoulos, A. Fragoulis, A. Kotronaros, D. P. Lalas, and I. Panourgias, “Turbulence measurements on top of a steep hill,” *J. Wind Eng. Ind. Aerodyn.*, vol. 39, pp. 343–355, 1992.

[29] J. C. Kaimal, J. C. Wyngaard, D. A. Haugen, O. R. Coté, Y. Izumi, S. J. Caughey, and C. J. Readings, “Turbulence Structure in the Convective Boundary Layer,” *Journal of the Atmospheric Sciences*, vol. 33, no. 11. pp. 2152–2169, 1976.

[30] J. Gottschall and J. Peinke, “Stochastic modelling of a wind turbine’s power output with special respect to turbulent dynamics,” *J. Phys. Conf. Ser.*, vol. 75, no. 1, p. 012045, 2007.

[31] E. Simiu and R. H. Scanlan, *Wind Effects on Structures: An Introduction to Wind Engineering*, Wiley. New York, 1986.

[32] K. M. Almohammadi, D. B. Ingham, L. Ma, and M. Pourkashanian, “Modeling dynamic stall of a straight blade vertical axis wind turbine,” *J. Fluids Struct.*, vol. 57, pp. 144–158, 2015.

[33] J. G. Leishman, *Principles of Helicopter Aerodynamics*, 2nd ed. Cambridge, UK: Cambridge University Press, 2000.

[34] M. Hölling, J. Peinke, and S. Ivanell, Eds., *Wind Energy - Impact of Turbulence*, vol. 2. Berlin, Heidelberg: Springer-Verlag, 2014.

[35] G. Buresti, *Elements of Fluid Dynamics*. London: Imperial College Press, 2012.

[36] C. Sicot, P. Devinant, S. Loyer, and J. Hureau, “Rotational and turbulence effects on a wind turbine blade. Investigation of the stall mechanisms,” *J. Wind Eng. Ind. Aerodyn.*, vol. 96, no. 8–9, pp. 1320–1331, 2008.

[37] W. A. Timmer, “Aerodynamic characteristics of wind turbine blade airfoils at high angles-of-attack,” in

TORQUE 2010: The Science of Making Torque from Wind, 2010, no. 1, pp. 71–78.

[38] J. L. Tangler, "Insight into wind turbine stall and post-stall aerodynamics," *Wind Energy*, vol. 7, no. May, pp. 247–260, 2004.

[39] C. Sicot, S. Aubrun, S. Loyer, and P. Devinant, "Unsteady characteristics of the static stall of an airfoil subjected to freestream turbulence level up to 16%," *Exp. Fluids*, vol. 41, no. 4, pp. 641–648, 2006.

[40] J. D. Sørensen and J. N. Sørensen, Eds., *Wind Energy Systems. Optimising Design and Construction for Safe and Reliable Operation*. Cambridge, UK: Woodhead Publishing Limited, 2011.

[41] V. Maldonado, L. Castillo, A. Thormann, and C. Meneveau, "The role of free stream turbulence with large integral scale on the aerodynamic performance of an experimental low Reynolds number S809 wind turbine blade," *J. Wind Eng. Ind. Aerodyn.*, vol. 142, pp. 246–257, 2015.

[42] E. E. Essel and M. F. Tachie, "Roughness effects on turbulent flow downstream of a backward facing step," *Flow, Turbul. Combust.*, vol. 94, pp. 125–153, 2015.

[43] M. Kiya and K. Sasaki, "Structure of a turbulent separation bubble," *J. Fluid Mech.*, vol. 137, no. -1, p. 83, Apr. 1985.

[44] K. Sasaki and M. Kiya, "Free-stream turbulence effects on a separation bubble," *J. Wind Eng. Ind. Aerodyn.*, vol. 14, no. 1–3, pp. 375–386, 1983.

[45] K. Sasaki and M. Kiya, "Effect of Free-Stream Turbulence on Turbulent Properties of a Separation-Reattachment Flow," *Bull. JSME*, vol. 28, no. 238, pp. 610–616, 1985.

[46] S. M. Hoffman, J. A., Kassir, S. M., and Larwood, "The Influence of Freestream Turbulence on Turbulent Boundary Layers with Mild Adverse Pressure Gradients," 1989.

[47] P. J. McKeough, "Effects of turbulence on aerofoils at high incidence," University of London, 1976.

[48] X. Amandolèse and E. Széchényi, "Experimental study of the effect of turbulence on a section model blade oscillating in stall," *Wind Energy*, vol. 7, no. 4, pp. 267–282, 2004.

[49] R. F. Huang and H. W. Lee, "Effects of Freestream Turbulence on Wing-Surface Flow and Aerodynamic Performance," *J. Aircr.*, vol. 36, no. 6, pp. 965–972, Nov. 1999.

[50] P. Devinant, T. Laverne, and J. Hureau, "Experimental study of wind-turbine airfoil aerodynamics in high turbulence," *J. Wind Eng. Ind. Aerodyn.*, vol. 90, no. 6, pp. 689–707, 2002.

[51] A. Gross, H. F. Fasel, T. Friederich, and M. J. Kloker, "Numerical investigation of rotational augmentation for S822 wind turbine airfoil," *Wind Energy*, vol. 15, no. 8, pp. 983–1007, 2012.

[52] S. Guntur, N. N. Sørensen, S. Schreck, and L. Bergami, "Modeling dynamic stall on wind turbine blades under rotationally augmented flow fields," *Wind Energy*, vol. 19, no. 3, pp. 383–397, Mar. 2016.

[53] W. D. Lubitz, "Impact of ambient turbulence on performance of a small wind turbine," *Renew. Energy*, vol. 61, pp. 69–73, 2014.

[54] L. Gilling, N. N. Sørensen, and L. Davidson, "Detached eddy simulations of an airfoil in turbulent inflow," in *47th AIAA Aerospace Science Meeting Including The New Horizons Forum and Aerospace Exposition*, 2009, pp. 1–13.

[55] C. C. Baniotopoulos and T. Stathopoulos, *Wind Effects on Buildings and Design of Wind-Sensitive Structures*. Wien: Springer-Verlag, 2007.

[56] F. Porté-Agel, H. Lu, and Y. Wu, "Interaction between Large Wind Farms and the Atmospheric Boundary Layer," *Procedia IUTAM*, vol. 10, no. 0, pp. 307–318, 2014.

[57] M. R. Luhur, J. Peinke, J. Schneemann, and M. Wächter, "Stochastic modeling of lift and drag dynamics under turbulent wind inflow conditions," *Wind Energy*, vol. 18, no. 2, pp. 317–337, Feb. 2015.

[58] H. S. Kang, S. Chester, and C. Meneveau, "Decaying turbulence in an active-grid-generated flow and comparisons with large-eddy simulation," *J. Fluid Mech.*, vol. 480, pp. 129–160, 2003.

[59] D. Mehta, A. H. van Zuijlen, B. Koren, J. G. Holierhoek, and H. Bijl, "Large Eddy Simulation of wind farm aerodynamics: A review," *J. Wind Eng. Ind. Aerodyn.*, vol. 133, pp. 1–17, 2014.

[60] N. Karthikeyan, K. Kalidasa Murugavel, S. Arun Kumar, and S. Rajakumar, "Review of aerodynamic developments on small horizontal axis wind turbine blade," *Renew. Sustain. Energy Rev.*, vol. 42, pp. 801–822, 2015.

[61] N. N. Sørensen, "CFD modelling of laminar-turbulent transition for airfoils and rotors using the γ- Rẽθ model," *Wind Energy*, vol. 12, no. April, pp. 715–733, 2009.

[62] J. N. Sørensen and W. Z. Shen, "Numerical Modeling of Wind Turbine Wakes," *J. Fluids Eng.*, vol. 124, no. 2, p. 393, 2002.

[63] Y.-T. Wu and F. Porté-Agel, "Atmospheric Turbulence Effects on Wind-Turbine Wakes: An LES Study," *Energies*, vol. 5, no. 12, pp. 5340–5362, 2012.

[64] M. O. L. Hansen, J. N. Sørensen, S. Voutsinas, N. N. Sørensen, and H. A. Madsen, "State of the art in wind turbine aerodynamics and aeroelasticity," *Prog. Aerosp. Sci.*, vol. 42, no. 4, pp. 285–330, Jun. 2006.