AdVanced Aerodynamic Tools for lArge Rotors

Perspectives and guidelines for up-scaling to 20MW wind turbines

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1. Introduction

The present document presents an outlook for the up-scaling of wind turbines into the 20 MW range. The aerodynamic and aeroelastic models and tools, which are the focus of the AVATAR project, will play a key role in the design of these giant machines. It is thus essential to discuss the validity and limits of these models, their strengths and needs for further development, in the light of what was learned during the AVATAR project.

Further, the AVATAR partners produced some design recommendations for very large wind turbines, and came up with guidelines for future aerodynamic experiments.

2. Validity of aero models

At the beginning of the AVATAR project, one aim was to test the validity of aerodynamic and aeroelastic models for a larger turbine, namely a 10 MW one, while the starting point was around 3-5 MW. Further, where weaknesses were identified, models and methods were to be improved using cross-comparisons with models of the same fidelity level, or input from higher-fidelity tools. Much was achieved, mostly by improving the accuracy level of the models, and reducing their uncertainties. The further up-scaling towards the 20 MW range will depend on many factors, including:

- Turbine architecture (horizontal vs. vertical axis, upstream vs. downstream rotor, three vs. n-bladed, single vs. multiple rotors, etc.)
- Turbine operation (e.g. low-induction blade aero, tip speed limitation, distributed flow control, aeroelastic coupling, etc.)
- Offshore vs. onshore turbine (noise, structural dynamics, etc.)
- Design drivers (loads, stability, etc.).

If the 20 MW turbine is a “scaled-up” version of today’s multi-MW machines, it is safe to assume that it can be designed with tools similar to the current ones. However, their accuracy should be further improved, and their uncertainty reduced, so that the turbine can operate more safely closer to known limits. On the one hand, any unnecessary safety factor would penalize the turbine and make it less attractive in terms of LCOE. On the other hand, a safety factor set too low would lead to a rapid failure. This is to some extent already the case today, but it is easier for current practices to err on the side of slightly bloated safety factors. This freedom will be very much limited with a 20 MW turbine, and the aero tools and models should help the designers to walk this much narrower path more safely.

If a “new” design concept is used for these very large wind turbines, it can be conjectured that the aerodynamic tools that will be used to design such turbines will at first not be significantly different from today’s ones, and will therefore have to deal with the same difficulties and problems.

The main uncertainties and related models are listed below.

Aerodynamic airfoil polars at very high Reynolds numbers. The results from the project indicate that current models may not be directly applicable for Re > $20x10^6$, which will be necessary for very large-scale wind turbines. Special care is required for the turbulence models, to ensure their suitability for the operating Reynolds number. In addition to that, specific issues that need to be addressed are related to:

- Computation of “clean” (transitional) and “tripped” (fully-turbulent) polars. Differences in both were seen for large blades. It is also important to determine when (and for how long) one can consider the blade clean and model its operation under these assumptions.
- Use of 2D polars in engineering models. In some cases, the correction parameters that are used may be insufficient for large blades.

- Derivation of 360° polars. This is an area where higher-fidelity models are needed, if we are to correctly capture the flow behavior at very large angles of attack. While this is not crucial to the performance of the blades, it is a factor that affects the stability and loading of the blades. For smaller, stiffer blades this was of no major consequence, but for large blades it seems that these errors are no longer acceptable, as they can lead to instabilities (or unnecessary over-engineering of components, if the worst-case results are followed).
- Dynamic stall modelling. Higher-fidelity models need to be used to model the flow accurately.

Effect of aerodynamic control devices. The cases of VGs and flaps were examined in this project, revealing difficulties related to the modelling of both. These are related to:

- Acquiring reliable static polar data, to be used as input for engineering codes in 3D simulations. For moving surfaces (flaps), this is relatively straightforward. The models used for vortex generators must be calibrated very carefully, in order to represent the 3D effects in a realistic way.
- Modelling of 3D effects from distributed control devices on the blade. It has been found that the actual 3D behavior of flaps and VGs is substantially different from the 2D models. If one needs to introduce these to engineering models, additional corrections will be needed for the modeling to be representative.

Non-linear aeroelastic behavior of long and slender blades. While investigating the aeroelastic behavior of the reference rotor in the AVATAR project, issues related to non-linearities of the blades were studied. Simpler computational tools that were in use for small blades will not suffice in this case. The proposed models should include:

- Blade structural models including modal superposition
- Coupling of improved structural models with multi-body simulation approach
- Models for vortex-induced vibrations in idling or parked conditions.

Effects of complex and turbulent inflow conditions on wind turbine performance. As the rotor diameter grows beyond 200m, it spans a vertical range with measurably different flow conditions (due to shear, veer, etc.). To simulate these effects, carefully chosen models must be applied for:

- Induction
- Yawed flow
- Shear
- Inflow (turbulence, wake).

It is very important to ensure the proper representation of these features in engineering models. In some cases, it may be necessary to resort to higher-fidelity models, in order to validate and calibrate the engineering models that are employed in the design phase.

Interaction of complex inflow with wind turbine dynamics and impact on performance. This is a direct consequence of the previous point, affecting the calculations related to the blades' stability and dynamic characteristics. Important aspects are:

- Stability analysis, performed through linearization and/or time-domain simulation, becomes more complicated, and additional care is needed to identify the resulting modes
- Relation between atmospheric and wind-turbine length scales changes, resulting in different interactions, that go beyond the current standard practice.

Control schemes for very large wind turbines (isolated and in farms). The actual issue of control was not addressed in the project, but the necessary underlying model was tested, in the form of *dynamic inflow models*. This is important for both isolated wind turbines (because of the increasing size of the rotor that is experiencing complex dynamic inflow) and wind farms (which extend to tens of kilometers, with increasing inter-turbine distances).

As stated above, it is necessary to keep improving the model accuracy and reduce or better understand their uncertainties. This does not come for free, and more high-quality experimental measurements (see section 4) and high-fidelity CFD simulations are required to achieve that goal. Note that databases from some intermediate fidelity models can also be used, which have demonstrated their ability to capture particular physical aspects (e.g. in the AVATAR project, free wake models have been proven able to capture the induction physics well).

The more the architecture of the 20 MW turbine differs from the conventional horizontal-axis, three-bladed machine with upstream rotor, the higher the need for new tools, that will at first come with increased uncertainties. This is one of the main reasons why the barrier to entry of radically new architectures is so high.

3. Design recommendations for large wind turbines

As of today, the largest wind turbines on the market approach the 10 MW mark. Looking ahead, the rated power keeps increasing, and no stringent limit for the growth of horizontal-axis 3-bladed turbines has been clearly identified and demonstrated yet, even if the topic is debated in heated discussions. In this context, a set of design recommendations for very large wind turbines has been gathered, based on the experience and engineering foresight of the AVATAR partners. They are summarized in Table 1, together with links to AVATAR work packages and tasks.

Guidelines	AVATAR links
Include blade induced twist into design	WP4
Include impact of higher Reynolds numbers (aerodynamic polars, airfoil design)	Tasks 2.1, 2.2, 2.3
Optimize thickness distribution (i.e. thicker airfoils in outboard region)	
Assess impact on stability of aerodynamic polar extrapolation to +/-180° (linked to dynamic stall model)	Task 1.3 & related workshop
Use realistic wind input for simulations (including shear, veer, turbulence modeling with proper spectral contents at low and high frequencies)	Tasks 2.4, 2.6, 4.2
Use fine enough blade discretization to deal with large deformation	
Perform cost trade-off analysis for inclusion of more carbon composites	
Assess impact of higher edgewise loads (gravity loads) on fatigue (e.g. vs. extreme loads)	
Assess impact of blade structural stability requirements (incl. idling and parked blade conditions)	
Assess impact of first flap mode having a higher amplitude because of shear	
Assess interactions between system frequencies and frequencies from excitation in normal operations (1P, 3P, etc.)	
Assess impact of long and heavy blades on pitch control (e.g. blade deformation, bandwidth for AOA control, drive wear)	
Assess usefulness of active aero to assist pitch system or alleviate extreme loads	WP3
Recognize that a simple scaling will not be sufficient, and look for new technologies (e.g. more carbon)	
Offshore: consider higher need for leading-edge erosion protection	
Large wind turbine farms require higher-fidelity flow modelling (incl. interaction with atmospheric boundary layer)	
Include airfoil & blade optimization for system value maximization (and lower LCOE)	

Table 1: Summary of design guidelines for very large wind turbines

Beyond the design aspects, some more general recommendations are given below:

- Adapt pre-bend (manufacturability issues with infusion when height difference becomes larger than 8m)
- Assess implications of very heavy blades (e.g. with cranes, handling)
- Assess implications of manufacturing limitations for spar-cap thickness (e.g. more carbon, broader spar caps)
- Consider using more modular concepts

4. Guidelines for future aerodynamic experiments

4.1 Background

The main goal of the EU AVATAR project is to improve aerodynamic and aeroelastic models of wind-turbine design codes for ratings up to 10 MW. Since wind turbines at the upper rating end do not exist (yet), model development and validation using true full-scale measurements are not possible. Consequently, model development and validation in AVATAR was performed using cross-comparisons between numerical simulation results, wind tunnel measurements and a limited number of (restricted) DANAERO 2 MW field measurements.

The AVATAR deliverable D1.8 deals with upscaling wind turbines towards the 20 MW range, for which the lack of experimental data is even more acute. This is the reason why the design of such an experiment was included, as written in the AVATAR Description of Work: "*The project will provide guidelines for a future Large-Scale Experiment formulated by ECN, DTU WIND, CENER, GE and LM. It will build upon the ideas for such experiment which has been generated within the subgroup aerodynamics of EERA where it was stated that lack of high-quality measurements on large wind turbines is one of the main bottlenecks in the wind energy society"*. In the following, guidelines for such experiment are provided, which include:

- the goal of the measurement project (4.3),
- the constraints and requirements (with emphasis on the size of the turbine to be considered and data confidentiality) (4.4),
- a global outline of the experiment (4.5).

This chapter also presents a historical overview and the state of the art in aerodynamic experiments.

It is noted that this document is intended to be a starting point for an activity which is included in phase IV of IEA Task 29. This 4th phase is supposed to start in January 2018. Thereto the project description of IEA Task 29, Phase VI writes "*The design of the experiment (in IEA Task 29) should be as complete as possible and it should include goal, requirements, target turbine but also details on sensors (prices, preferred suppliers etc.), design of instrumentation, detailed test matrix, supporting experiments etc.* ***It will be much more elaborate and detailed*** *than a description of a field experiment which is currently being made within the AVATAR project and it should reduce the preparation time for a possible experiment to an absolute minimum. The availability of a well thought out plan from the mondial aerodynamic society and the minimal preparation time to an experiment might facilitate a positive decision for resources from e.g. the EU*."

4.2 Aerodynamic experiments: historical overview and state of the art

Conventional experimental programs on wind turbines generally measure the integrated, total (blade or rotor) loads. These loads consist of an aerodynamic and a mass-induced component and they are integrated over a certain spanwise length.

In the late 80’s and the 90’s, it was realized that more direct aerodynamic information was needed to improve the aerodynamic modelling. For this reason, several institutes initiated experimental programs in which pressure distribution and the resulting normal and tangential forces at different radial positions were measured on the blades. Under the auspices of the IEA Wind, many of these measurements were stored into a database in Task XIV and Task XVIII, see 20[1] and Figure 1. The results of these measurements turned out to be very useful and important new insights on e.g. 3D stall effects, tip effects and yaw were gained.

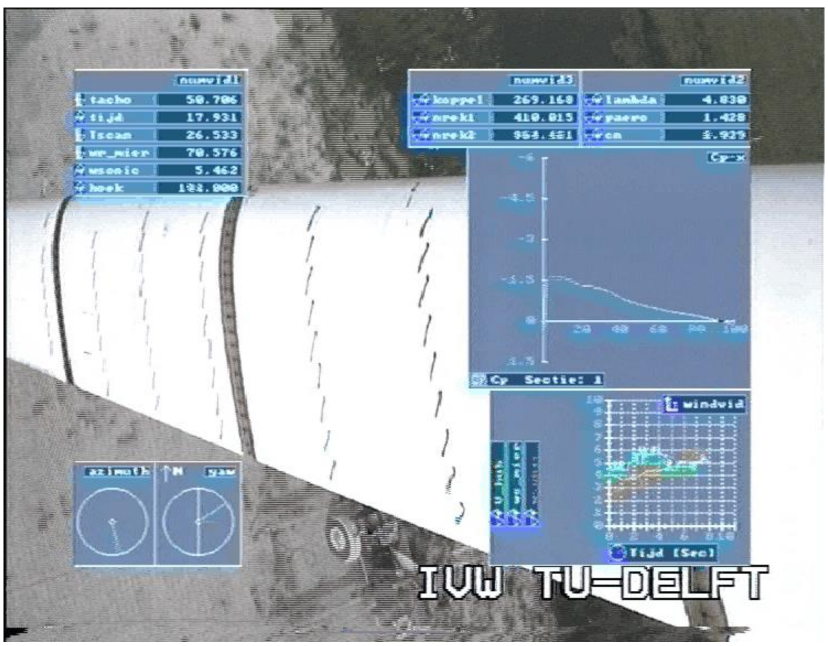

Figure 1: TU Delft experiment as contributed to IEA Task XIV/XVIII, showing the instrumented blade as recorded from a camera on the hub.

However, the IEA Task XIV/XVIII measurements were performed on turbines in the field, where uncertainties in the unsteady, inhomogeneous and uncontrolled wind conditions are inevitable. Therefore, the insight grew that aerodynamic field measurements should be complemented with aerodynamic wind tunnel measurements. Very important in this respect were the NREL measurements on a 10-meter diameter turbine as performed in the year 2000, see Figure 2. These measurements were analyzed within IEA Task XX [2]. This was followed by a wind tunnel experiment in 2006 carried out within the EU project Mexico, where measurements were taken on a 4.5-meter diameter turbine placed in the German Dutch Wind Tunnel DNW, see Figure 3. Beside measurements of pressure distributions along the blade, the entire flow-field around the turbine was mapped using the Particle Image Velocimetry technique. The Mexico measurements were analyzed within IEA Task 29 [3].

Figure 2: NREL experiment in the NASA Ames wind tunnel.

The wind tunnel measurements from NASA Ames and Mexico led to a much better understanding of several aerodynamic phenomena, as wind-tunnel measurements obviously have the advantage of constant, known and controllable conditions, where the Mexico measurements proved that it is even possible to map the entire flow field, with all its detail, around the turbine.

Wind tunnel measurements however do suffer from tunnel and scaling effects. Even the large experiment at NASA Ames was done on a rotor with a diameter of 10 meters, which is at least a factor 20 smaller than the rotor diameters considered in D1.8, thus leading to Reynolds numbers which are approximately 20 times smaller. Moreover, the constant and uniform conditions, though very helpful to interpret the results, are not representative of the real conditions as felt by a large-scale wind turbine. As a matter of fact, this problem is related to size: many aerodynamic response models do not account properly for the incoherencies and turbulent structures in the atmospheric inflow since they implicitly assume uniform conditions. Such assumption is valid for the above-mentioned wind tunnel experiments. It is to some extent still valid for **small** turbines in atmospheric conditions since the flow incoherencies within a small rotor plane are limited. However, the stronger incoherencies for larger rotors make the relationship between the relevant scales in the atmospheric inflow to the aeroelastic scales much more challenging.

Besides, the aeroelastic effects of large rotors in atmospheric flow will be much more challenging due to the larger blade deflections and more pronounced non-linear aeroelastic behavior with unknown aerodynamic implications. Hence, it is obvious that wind-tunnel measurements and field measurements (on large-scale rotors) should complement each other.

Figure 3: Set-up of the Mexico model in the LLF tunnel of DNW.

The main (public) aerodynamic field database (i.e. from IEA Task XIV/XVIII) was created in the early 90's using small turbines (most rotor diameters were in the range of 10-20 m) with relatively old measurement techniques. Unfortunately, no boundary-layer details were obtained, even though the boundary layer is very determinant for the pressure distribution, the drag and the noise of a wind turbine. Besides, the inflow was very poorly mapped.

More recently, aerodynamic field measurements on a full-scale 2.5 MW turbine have been carried out within the Danish DANAERO MW experiment in a collaboration between Vestas, Siemens, LM, DONG Energy and Risø DTU. Surface pressure and inflow were measured at four sections along the blade span, see Figure 4. Additionally, a row of flush-mounted surface microphones were installed at the outer section (see Figure 5),enabling the study of boundary-layer transition and the surface pressure spectrum, which is the source of trailing-edge noise [4][5]. However, due to the considerable own funding from the partners, the data are until now not publicly available yet, though they are expected to be released in the above-mentioned 4th phase of IEA Task 29.

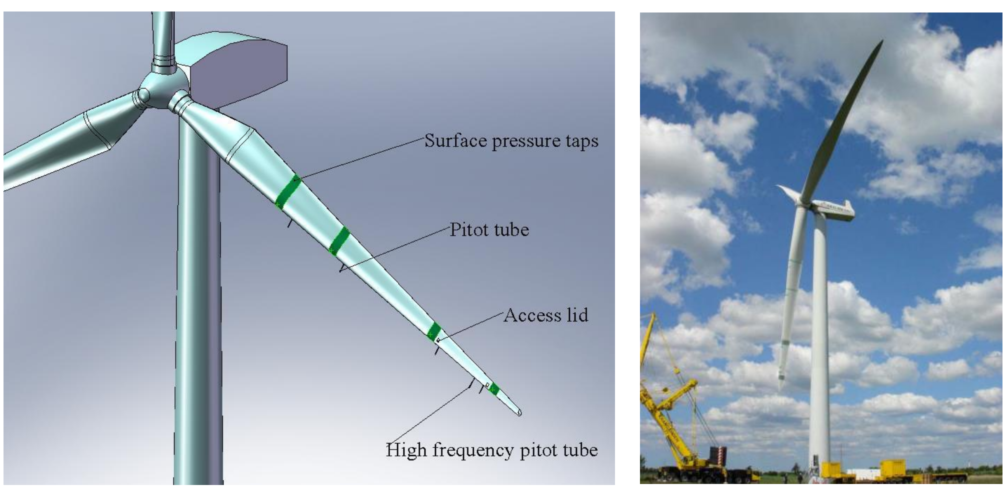

Figure 4: Sketch of the instrumented LM38.8 m blade (left), NM80 turbine with the test blade installed on May 13, 2009 (right).

Figure 5: About 50 microphones were installed about one millimeter below the blade surface on the outboard section at radius 37 m for high frequency surface pressure measurements.

It is thus about time for a new joint field aerodynamic measurement program on a larger scale rotor, the data of which should be accessible to the entire European research society.

It is noted that acoustics and aerodynamics are closely interrelated. Within the EU projects DATA, Sirocco and New Mexico, detailed acoustic measurements have been performed on wind turbines [5]. The present experiment forms a perfect opportunity to combine both acoustic and aerodynamic measurements.

4.3 Goal

The main goal of the experiment considered in the present deliverable is to perform a **public** aerodynamic field experiment on a large-scale wind turbine using the most advanced aerodynamic (and acoustic) measurement techniques. The data will be analyzed and used to validate and improve aerodynamic, aeroelastic and acoustic wind-turbine design tools. More specifically, the experiment should focus on the validation and improvement of models for:

- aerodynamic response to turbulent inflow,
- sheared and yawed inflow,
- 2D/3D airfoil characteristics,
- aeroelastic effects,
- wake-flow operation,
- boundary-layer transition characteristics in realistic flow conditions,
- noise source characterization,
- stand-still conditions.

To assure a high-quality experiment which serves the needs of the wind-turbine aerodynamic research community, the experiment is carried out by a large consortium in which many members of this research community are involved.

4.4 Constraints and requirements

4.4.1 Scale

An important requirement lies on the scale of the turbine. AVATAR deliverable 1.8 mentions the turbine to be in the range from 10 to 20 MW. Measurements on such a scale are not very realistic to achieve in the short or mid-term since such turbines are not on the market yet. This implies that the experiment could wait until turbines of this size have become available. However, instead of waiting, it is preferred to do concessions on size and/or rated power.

It should then be realized that rated power has an ambiguous relation to scale. On the one hand, there is a trend towards lower power densities which increases the rotor size for a given rated power. On the other hand, there is a trend from manufacturers to upgrade the rated power without changing the rotor size. For example, the Enercon E-126 turbine entered the market in 2007 with a rated power of 6 MW, but nowadays it has a rated power of 7.5 MW without change in rotor diameter. Another example is the Vestas V164 which entered the market in 2011 as 7 MW turbine, and which is now built for a rated power of 9.5 MW.

Although the present deliverable has mentioned a rated power of 10-20MW as determinant criterion, it is thus the rotor size which, in the context of aerodynamic and aeroelastic modelling, is considered more important than rated power. This scale dependency is not only related to Reynolds number, but also to the changed relation between the scales in atmospheric inflow to the scales of the turbine (blades). The larger deflections make the aerodynamic response modelling of large turbines much more challenging too. In D4.6, it is found that more physical aerodynamic models give up to 10-20% lower fatigue loads than BEM-calculated fatigue loads, which is partly expected to be caused by the more local tracking of the induced velocities in the physical models.

During the AVATAR meeting at CENER, it was agreed that the minimal rotor diameter of the experiment to be considered should be 100 meters. The maximal chord-based Reynolds number along the blade should at least be on the order of 1.0e7.

4.4.2 Location

Although AVATAR is focused on offshore wind, a turbine at an onshore location should be considered for the present purpose. Carrying out this kind of detailed experiments will e.g. require access to the blade for mounting sensors and instruments and this will not be realistic offshore. The inflow at offshore conditions differs from those at onshore ones, however all relevant phenomena on shear, turbulence, wake flow, stability could be covered onshore.

4.4.3 Measurement time

Measurements should be collected over a long period of at least two years. This is not only needed to determine phenomena with sufficient statistical certainty, but also to catch very rare atmospheric conditions and their aerodynamic response (e.g. extreme shears, incoherent structures, etc.). A long measurement time is also helpful to include the inevitable lessons learnt in the early phase of the experiment into later campaigns and to pay back the large investment.

4.4.4 Goal

The present guidelines focus on validation and improvement of aerodynamic, aeroelastic and acoustic models. Research directed at demonstrating and testing aerodynamic innovations and devices is not included, even though the heavily instrumented turbine from this document will form a perfect test bed for such demonstration and testing. It is noted that the distinction between modelling and demonstration is in line with the distinction between AVATAR (with its focus on modelling) and INNWIND.EU (with its focus on innovations).

4.4.5 Turbine data

We noted above (4.3) that the experiment should be public. Public in this sense does not only mean that the measurement data may be released, but for validation purposes it is equally important that the underlying turbine model description is published as well. In the present context, it is believed that the aerodynamic and aeroelastic blade data are most essential. Usually those data are protected and they can be released after very lengthy negotiations on NDAs only (as was the case with the DANAERO experiment in AVATAR). At the AVATAR meeting at NTUA, it was suggested to design a tailor-made research blade according to the wishes of the research society. Such blade can then be built by a manufacturer, e.g. LM, but the ownership of the blade data remains at the research consortium by which the confidentiality issue from a commercial blade is overcome. A remaining confidentiality item may be the turbine controller. This issue will depend on the turbine on which the blades are mounted. Most likely this will be an existing turbine with a protected control algorithm. If the algorithm cannot be released and if a protection through

NDAs is not possible either it might be sufficient to use the measured rotor speed and pitch angle as function of time and wind speed only.

Note that it might make sense for the research community to engage closely with the wind industry to determine whether an older but still relevant platform could be declassified and used as research instrument. This is obviously a longer-term effort, but if successful, it might lessen much of the above-mentioned constraints.

4.5 Approach

The project will be performed in several steps where steps 1 to 5 and step 7 are foreseen to be covered (partly) in an IEA Task. Steps 6, 8 and 9 require more funds which are not secured yet.

1. **Definition of research questions to be answered**. In global terms, this is already covered by the text above, but a more elaborate document will be prepared which very specifically defines and quantifies the research questions. This document will serve as input for the design of the experiment.
2. **Turbine selection**. A large-scale wind turbine will be sought on which the blades from step 3 can be placed.
3. **Blade design**. This will be performed by the consortium.
4. **Inventory of measurement techniques**. As a minimum, the following measurements will be considered:
   - pressure (and load) measurements along the blade,
   - boundary-layer measurements (transition, shear stresses),
   - blade deformation (bending, twisting),
   - flow-field measurements (inflow and near wake),
   - acoustic measurements.

   Note that within IEA Task XIV/XVIII, NASA Ames, Mexico, DANAERO and Sirocco the following measurement techniques have been used:

   a) Pressure measurement techniques: In most of the above-mentioned experiments, pressures distributions were measured with fast scanners, which generally measured differential pressures. Damping in the tubes and uncertainty in the reference pressure are problems associated with this measurement technique. In the Mexico experiment in-situ absolute pressure transducers have been used.
   b) Inflow measurement techniques: In field tests, the inflow has generally been measured with a limited number of anemometers (either cup or sonic anemometers), where the DANAERO experiment also used a LIDAR. In some experiments, the inflow at a limited number of blade sections has been measured with 5-hole pitot probes. Within the Mexico experiment, the inflow (and wake) has been mapped with Particle Image Velocimetry (PIV).

c) Boundary layer measurement techniques: Within the DANAERO experiment, transition was measured with microphones.
d) Acoustic measurement techniques: Within the DATA and Sirocco projects, detailed acoustic measurements of the noise sources in the rotor plane have been performed with an acoustic array placed upstream of the turbine. In the DANAERO project, the boundary-layer surface pressure spectrum, which is the source of the turbulent trailing-edge noise, was measured.

The above-mentioned measurement techniques remain important candidates for the present experiment, but new measurement techniques available from other areas (e.g. aerospace) will also be considered. Thereto the potential of the most advanced measurement techniques for wind turbine applications will be assessed.

5. **Definition of specifications for the instrumentation and the processing**. On the basis of these specifications, the experimental set-up will be designed.
6. **Building, instrumentation, DAQ and testing**. This includes the blade instrumentation, e.g. drilling pressure holes, implementation of pressure transducers and DAQ units, transfer of data from the rotating to the fixed world, development of process software, etc. The instrumented blades are placed on the turbine and tested.
7. **Definition of test matrix**. The test matrix serves as a handbook for the execution of the measurements. It describes the actions needed for every data point, the measurement conditions, the measurement times etc.
8. **Execution of measurements**.
9. **Analysis and interpretation of results**. These activities will already start as soon as the first data from task 7 flow in, i.e. the analysis of results takes place during the experiment by which the lessons learnt from the first campaigns can be incorporated in later campaigns. A comparison of results with previous experiments (e.g. field measurements from IEA Task XIV/XVIII and the NASA Ames/Mexico wind tunnel measurements) forms part of the analysis.

5. Conclusions

Even if the first 20 MW wind turbine looks like an older sister of the current horizontal-axis, three-bladed multi-MW machines, it will not be a “simple” scale-up of the latter. It will have to benefit from a significant injection of new technologies, related to e.g. materials, aero and structural design, controls and operations. The related design tools will probably resemble the ones used today, but they will need to be much more accurate and have reduced uncertainties, so that the 20 MW turbine can operate safely and efficiently without unnecessary safety margins.

To support the required evolution of the design tools, it is essential to accumulate calibration and validation data of sufficiently high quality and covering “adequately” the design space. Obviously, some extrapolation to the final design space would still be required, but care should be taken that this “jump into the unknown” is as small as possible. This high-quality data can come from numerical simulations or experiments. Both have their strength and weaknesses, but when combined, offer a strong base to improve our physical understanding and enhance our models.

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