AdVanced Aerodynamic Tools for lArge Rotors

Coordination of Wind Tunnel Measurements

Ozlem Ceyhan , ECN
Jesper Madsen , LMWindPower
Michael Hoelling, Oldenburg University
Hendrik Heißelmann, Oldenburg University
Niels Sørensen, DTU Wind
Oscar Pires, CENER
Xabier Munduate, CENER

Review by Gerard Schepers, ECN

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1. Introduction

The objective of the present work is twofold.
On the one hand a set of specifications describing the wind tunnels, the test set up, the model, the corrections and the output results is implemented as a guarantee that the execution of the different tests will accomplish a reasonable and common level of specifications that will help to guarantee the employment of the results. This is especially useful once the tests have been completed, and the resulting data are ready to be evaluated and later validated with theoretical and numerical tools. The above is what compounds this deliverable.
The second objective, which will be ready at the end of the execution of the wind tunnel tests goes into the target of obtaining and compiling a database of wind tunnel experiments with a clear orientation towards validation of aerodynamic tools. Thus, the building of the database would be constructed with the requirements (model, flow and post processing specifications) that high level codes need or will implement in the short term in order to be able to simulate more exactly the conditions of the test. This is obviously, but sometimes difficult to accomplish, the first stage towards advancing into the development of new aerodynamic models and tools.

The present report is composed from contributions of different partners. They were all asked to provide their information in the following format:

- Test objectives
- Wind tunnel description
    - Test section
    - Flow conditions
    - Instrumentation
- Test description
    - Measurements
    - Instrumentation techniques
    - Corrections
    - Models
        - Aerofoil name
        - Instrumentation
        - Materials
        - Tolerances
    - Testing procedure
        - Alfa range
        - ….
        - Repeatability
    - Test matrix
    - Output data format
- Test incidences

2. High Reynolds Low Mach – DNW HDG test (Ozlem Ceyhan)

2.1 Introduction

One 2D Airfoil models is going to be tested at the DNW High-Pressure Wind Tunnel at Gottingen (HDG). The model will have a chord of 0.15 meters and a span of 0.6 m and will be instrumented with a maximum number of 90 pressure taps.

The first objective of the tests is to investigate the effects of high Reynolds numbers on thick wind turbine airfoils by wind tunnel testing. Second objective is by using the results of these tests validate/improve existing (transition) prediction models for high Reynolds numbers at low Mach numbers, and this work will be done after the tests in Avatar project.

2.2 Wind Tunnel Specifications

The High Pressure Wind Tunnel at Göttingen (HDG) is a closed return continuously operating, low speed wind tunnel. The whole tunnel circuit including plenum chamber can be pressurized up to 100 bar (10 MPa), in order to give raise to Reynolds number variability by a factor of 100. The fan is driven by an 470 kW electric motor, located outside of the pressurized shell. Air speed is varied by rpm regulation of the constant pitch fan.

Key Technical Parameters		
Test section	Cross section	0.6 x 0.6 m^2
	Length	1.0m
Performance parameters	Total pressure (max)	100 x 10^5 Pa (100 bar)
	Temperature range	Ambient (controlled)
	Speed range	3.5 - 35.0 m/s
	Reynolds num. (Lref=0.15m)*	$18x10^6$

*: This is the max Re number value that is aimed to be achieved during the Avatar tests.

2.3 Test Description

In the test description, some of the values depend on the airfoil selection and the priorities. Therefore they are kept as TBC-to be communicated and TBD- to be determined.

2.3.1 Test conditions

The model will be tested at 6 different Reynolds Numbers:

- 3 millions
- 6 millions
- 9 millions
- 12 millions
- 15 millions
- 18 millions or maximum achievable Reynolds number

For each of those Reynolds numbers, different model surface conditions will be tested: clean and transition tripped

At the clean condition the models will be tested with their entire surface as much clean as possible, free of any dirt.

The transition tripped condition will be simulated with the use of transition dots of size (TBD) and height (TBD)

In case of time constraints, number of Reynolds numbers to be tested will be decided depending on the priorities.

2.3.2 Angle of attack range

The angle of attack range will be –15º to 20º (TBC). Measurements will be taken for at least 45 angles of attack within this range.

2.3.3 High angle of attack range

Polars at high angle of attack range (-180º to 180º) will be taken at three different Reynolds numbers. The final decision about whether to include these condition to the test matrix or not will be given at the later stages of the project.

2.3.4 Repeatability checks

Repeatability checks within a polar and long term repeatability checks between different polars will be performed.

2.3.5 Instrumentation

- The model will be instrumented with a maximum number of 90 pressure taps distributed along the chord in order to measure the pressure distributions over the aerofoil. These pressure taps are connected to pressure scanners by means of tubes implemented in the 15 cm chord airfoil
- 5 electronic Kulite devices are added to give an indication on the state of the boundary layer. The Kulite sensors will be recalibrated by DNW in order to accommodate the current (pressurized) conditions.
- The wind tunnel will provide a traversable wake rake with 118 total and 8 static pressure probes in order to characterize the downstream aerofoil wake.
- Wall pressure distribution as well as 3 component balance force data will additionally be acquired to support result interpretation.

- The wind tunnel will be equipped with the needed instrumentation to measure and/or calculate the free stream wind conditions at the test section, such as wind speed, total and static pressure, dynamic pressure, temperature, etc.

2.3.6 Flow visualization

Flow visualizations will be performed in order to get information on airfoil transition and stall phenomena. The best available visualization technique will be used (china clay, fluorescence coloured oil, …). Installation of a camera inside the test section will be foreseen for the visualizations.

2.3.7 Inflow turbulence measurements

Inflow turbulence measurements on empty test section and/or during the measurement campaign will be performed. In case dedicated inflow turbulence measurements on the empty test section, the measurements should be provided for the possible pressure-velocity couples that will be covered during the Avatar tests.

The measurements should ideally be provided in different positions in the wind tunnel in order to cover the area where the model is installed normally.

The sensors that will be used for these measurements should be able to cover the sufficient frequency range of the relevant turbulence levels in the test section.

2.3.8 Draft Test Matrix

According to the requirements above, a test matrix is drafted. The final matrix will be decided later. Two pressure-velocity couples for each Re number to be tested is put in the test matrix in order to check the repeatability and the differences in the tunnel inflow turbulence.

	Condition One				Condition Two							
Reynolds	No	PT	q_∞	U_∞	No	PT	q_∞	U_∞	Surface condition		AoA range	Comments
(Mio.)		(bar)	(bar)	(m/s)		(bar)	(bar)	(m/s)	Type	Position		
3.0	2	34	0.02	10.0	1	20	0.03	17.0	Clean	-	-15º to 20º	
6.0	3	34	0.08	20.0	5	72	0.04	10.0	Clean	-	-15º to 20º	
9.0	4	34	0.17	30.0	6	72	0.09	14.8	Clean	-	-15º to 20º	
12.0	10	80	0.15	18.0	7	72	0.16	19.8	Clean	-	-15º to 20º	
15.0	11	80	0.23	22.5	8	72	0.25	24.8	Clean	-	-15º to 20º	
18.0	12	80	0.33	27.0	9	72	0.38	30.5	Clean	-	-15º to 20º	
3.0	16	34	0.02	10.0					Clean	-	α_1, α_2, α_3,…	Visualization
9.0	17	72	0.09	14.8					Clean	-	α_1, α_2, α_3,…	Visualization
15.0	18	72	0.25	24.8					Clean	-	α_1, α_2, α_3,…	Visualization
3.0	12	34	0.02	10.0					Tripped	P	-15º to 20º	
9.0	13	72	0.09	14.8					Tripped	P	-15º to 20º	
12.0	14	72	0.16	19.8					Tripped	P	-15º to 20º	
15.0	15	72	0.25	24.8					Tripped	P	-15º to 20º	

2.4 Data

2.4.1 Delivered data

All the test data will be delivered in electronic format.

Data files will contain at least the following information for each test condition and at all the measured angles of attack:

- Overall Lift, Drag and Pitching moment Coefficients and their components from pressure and wake rake measurements Aerofoil normal and tangential force coefficients and their components.
- Pressure coefficient values from each model pressure tap.
- Dynamic pressure values.
- Total and static pressure values from the wake rake probes.
- Test section free stream wind speed, Mach number, Reynolds number, dynamic pressure, static pressure, total temperature
- Pictures from visualizations

For all the above data that need the application of wind tunnel corrections, the following information will be included in the data files:

- Raw data (measured values without corrections)
- Wind tunnel corrections (supplied by DNW)
- Usable corrected data

All data files headers, definitions, parameters, explanations, etc, will be written in English language.

Turbulence intensity level of the wind tunnel will also be reported. It will include three (TBC) fluctuating velocity components (in m/s units) and their RMS values in time series and in frequency domain i.e. the spectra.

File formats of the data files will be decided between Avatar and DNW.

2.4.2 Online data

During the performance of the tests, customers who are present during the tests will have access to the online data such as aerodynamic coefficients and pressure distributions for the quality check of the test performance.

2.5 Model

The wind tunnel model will be delivered by DNW. The model quality should be sufficient for Avatar project goals.

The model must comply at least with the following specifications:

2.5.1 Geometry

The model will have a constant chord length along the span with:

Chord Length (c): 0.15 meters

Span Width (l): 0.6 meters

The selected airfoil is DU00-W-212. The main advantage of this airfoil lies in the pronounced laminar drag bucket with a different behavior between positive and negative angle of attacks, which helps to calibrate the critical N factor and the transition location in case this turns out to be difficult from the pressure distribution (experience University of Stuttgart). In this respect it must be noted that the aim of the experiment is to provide a database for model validation, the airfoil doesn't need to be used on the AVATAR RWT.

Trailing edge thickness: depending on the airfoil selected. It should have enough space to accommodate a pressure tap. However, it should be included to the CAD model to be approved.

The geometry of the airfoil is defined by the costumer in text data files. After the geometry is delivered by the customer, before the manufacturing, there will be a design approval between the customer and DNW. Design approval will be done during a teleconference. CAD model of the wind tunnel model will be checked and approved by the customer. In order to do this, CAD model will be sent at least two days in advance to the customer to be evaluated. It will be approved during the teleconference. After the model approval, all the changes to this CAD model should be communicated.

2.5.2 Instrumentation

The model will be instrumented with a maximum number of 90 pressure taps at the mid span section.

The pressure taps will have a diameter of 0.2 mm. and will be distributed at different span sections in order to avoid pressure readings disturbed by upstream pressure taps.

The position of the pressure taps on the model will be supplied by the customer, agreed with DNW, and delivered in text data files. One pressure tap will be put at the trailing edge of the model.

There will be extra five locations used for dynamic pressure measurements. Dynamic pressures will be measured with Kulite sensors.

2.5.3 Tolerances

General profile tolerances:	±0.05 mm.
General surface roughness:	Rz = 0.2 µm
Chord/span limits:	±0.1 mm

No steps at joints

A geometry inspection of all the models will be performed to check tolerance deviations. The contour check will be performed in at least 7 sections, measuring for each section a minimum of 300 points.

Roughness measurements of the models will be taken at 6 positions.

An inspection report including measured points, and deviations from tolerance will be delivered before the beginning of the wind tunnel tests.

2.6 Deliverables

- One 2D airfoil models instrumented with pressure taps
- CAD model of the wind tunnel model for model approval
- Geometry inspection report of the models in electronic format
- Box for model transportation
- Test data in electronic format
- Test report with the post-processed test data, no later than one month after end of the tests

2.7 Time Schedule

Wind tunnel and model set up will take place from 8th to 12th of September 2014. The test will be held from 15th to 30th of September 2014.

3. Dynamic Moderate Reynolds Moderate Mach – LMWind test (Jesper Madsen)

3.1 Test objectives

The objectives of the wind tunnel tests at the Low Speed Wind Tunnel (LSWT) of LM Wind Power are as follows:

- Transition Point determination on DU 91-W2-250
- Research on effects of tunnel parameters on transition location using cylinder and DU 91-W2-250
- Moderate to High Reynolds Number measurements (~6 Million) on DU 00-W-212 for comparison with Göttingen DNW-HDG measurements
- Dynamic AOA measurements on DU 00-W-212

3.2 Wind tunnel description

3.2.1 Test section

The test section of the LSWT has dimensions of 1.35 meters width, 2.7 meters height and 7 meters long. Using a model with a chord of 900 mm, a Reynolds number of 6 million can be achieved. Below is an overview of the LSWT test section set-up.

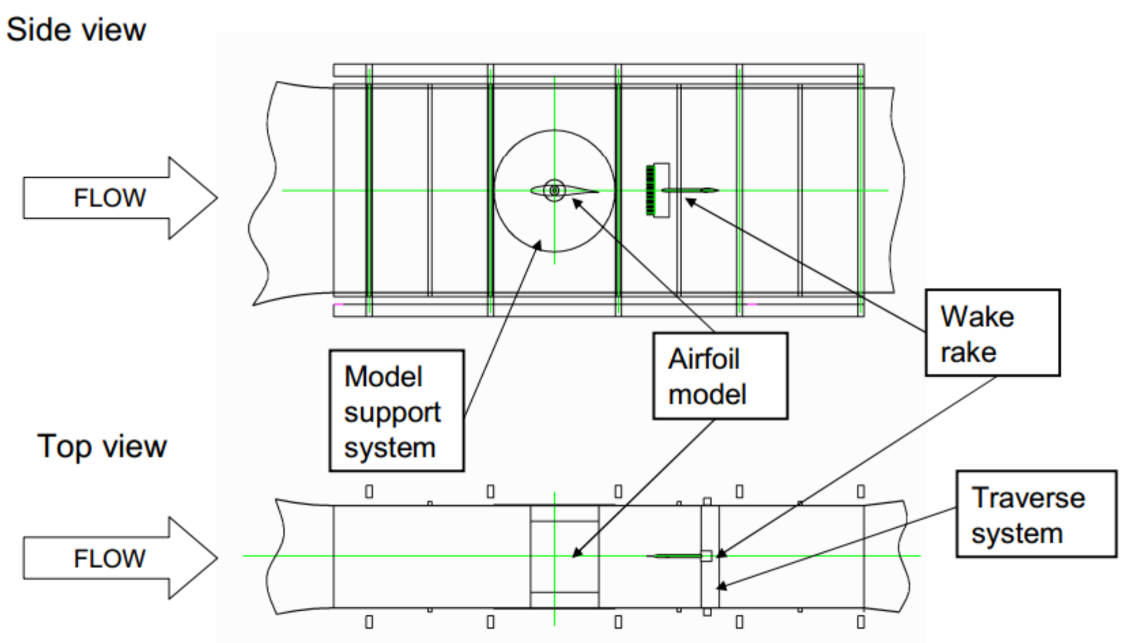

Figure 3-1: Test section set-up for the LSWT

3.2.2 Flow conditions

The flow in the test section is temperature controlled with variations ≤ ±0.5 °C. The flow speed can be set a maximum of 380 km/h where the velocity variation is less than 0.25% for any condition. Below a summary of the flow conditions:

- In a single point at the model leading edge:
  - Temperature variation less than ΔT ≤ ±0.5 °C.
  - Velocity variation of less than $\Delta u/u_0 \leq 0.25\%$ for all operation velocities
- In the model leading edge plane:
  - Flow velocity uniformity: $\Delta u/u_0 \leq 0.25\%$
  - Total pressure uniformity: Δq/q0 ≤ 0.2%
  - Temperature uniformity: ΔT ≤ ±0.25 °C
  - Maximum flow angularity in vertical and horizontal plane: α ≤ ±0.1°, γ ≤ ±0.1°
  - Maximum turbulence level (total turbulence): $|T_{utot}| \leq 0.1\%$
- On the test section center line:
  - Axial static pressure gradient (global value): $\Delta cp/\Delta x \leq 0.01\ m^{-1}$

3.2.3 Instrumentation

The LSWT and the used models have the following instrumentation available:

- Turn Table to rotate the model with possibility of obtaining all angles of attack;
- 6 Load Cells for obtaining all 3 2D force components;
- Airfoil Pressure Tabs to obtain a surface pressure distribution, this can be integrated to find the 3 2D force components;
- Wall Pressure Tabs in the floor and ceiling to obtain the lift force;
- Traversing Wake rake to obtain the velocity deficit, is used to calculate the drag force
- Infrared Camera, to visualize the boundary layer on some models.

3.3 Test description

3.3.1 Measurements

Currently 4 wind tunnel tests are of interest:

1. High Reynolds Number test of DU 00-W-212
2. Transition point research on a Cylinder
3. Transition point research on DU 91-W2-250
4. Dynamic AOA measurements likely on DU 00-W-212

3.3.2 Instrumentation techniques

The suggested tests are measured with the before mentioned instrumentation and additionally the use of visualization techniques (fluorescent tufts, oil, smoke, infrared camera, etc.) or a new instrument type (5-hole probe, high response probe, surface microphone, etc.)

3.3.3 Corrections

All wind tunnel tests are corrected for wind tunnel effects using the standards given in AGARD, AGARD-AG-336 Wind Tunnel Wall Corrections, Ewald B.F.R., 1998. Wall corrections work well for angles of attack up to around ±20°. However, currently work is ongoing to expand this range to ±180°.

3.3.4 Models

The following 4 models are to be used:

1. DU 91-W2-250
    a. Model is already manufactured
    b. The model has 64 surface pressure tabs in the center
    c. The model has been manufactured in aluminum with chord 600 mm
    d. Tolerances of the LSWT models are generally below ±0.5 mm
2. DU 91-W2-250
    a. Model is already manufactured
    b. The model has 64 surface pressure tabs in the center
    c. The model has been manufactured in carbon fiber with chord 900 mm
    d. Tolerances of the LSWT models are generally below ±0.5 mm
3. DU 00-W-212
    a. This model is not manufactured yet
    b. Geometry and pressure tab distribution will be aligned with model for the DNW-HDG tunnel
    c. The model will likely be manufactured in aluminum with chord 900 mm
    d. Tolerances of the LSWT models are generally below ±0.5 mm
4. Cylinder
    a. This model is not manufactured yet
    b. It is suggested to have at least 64 surface pressure tabs in sweep direction; furthermore surface microphones will give better insight in the transition location
    c. The model will likely be manufactured in aluminum with chord likely 450 mm
    d. Tolerances of the LSWT models are generally below ±0.5 mm

3.3.5 Testing procedure

The tests are performed fully automatic. The tunnel is directed by software where the test procedure is described. This ensures that any similar test in the future is performed similarly to obtain repeatability. Generally the airfoil model is rotated before Cl-Max up to above stall and back to below negative stall. This will capture any hysteresis effects. Deviation can be made for special tests or special angles of interest.

Wake rake measurements are performed by a sweep in cross sectional direction and averaging the values of drag measured by the wake rake. This is only performed in cases where the velocity deficit can be captured without too large fluctuation on the rake.

As a part of the AVATAR project dynamic AOA measurement instrumentation and testing procedures will be developed. The aim for the setup is to obtain test capabilities for reduced frequencies up to 0.2 (4 Hz) and an AOA amplitude of ±5°.

3.3.6 Test matrix

No test matrix has been generated yet. In general a test matrix will contain clean airfoil and airfoil with zigzag tape to emulate roughness. Furthermore, airfoils will be tested with devices like Vortex Generators, Gurney flaps, and maybe (static) flaps.

The tests for the DU 00-W-212 will, where possible, be similar to that of the matrix in the DNW-HDG.

3.3.7 Output data format

The output is stored in our in-house database by default and can be exported in many formats. Most likely format is CSV, data- or Worksheet files. Data will consist of CL, CD, CM, Cp on center, and for DU 91-W2-250 furthermore transition point location.

3.4 Time Schedule

The tests will be performed in separate campaigns each covering several days. Main aim is to put each of the 4 measurements described in section 3.3.1 in a separate campaign.

LM wind tunnel activities and estimated test plan:

Overall budget:

- 4 wind tunnel models
- 4 measurement campaigns of 12 days each

Test plan (rough estimate):

- Q4-2014:
  - Campaign DU 00-W-212: Comparison to DNW-HDG high Reynolds number tests
  - Campaign DU 91-W2-250: Transition point location
  - Preparation of wind tunnel control system and instrumentation for dynamic measurements
- Q1-2015:
  - Testing of dynamic measurement setup
- Q3-2015:
  - Campaign DU 00-W-212: Dynamic AOA measurements
- Q2-2016:
  - Campaign Cylinder: Measurement of drag and transition point on cylinder

4. Turbulence Inflow at Low Reynolds - Oldenburg University test (Michael Hoelling, Hendrik Heißelmann)

4.1 Test objectives

The planned experiments in AVATAR are aiming at the identification of the influence of turbulence on the aerodynamic characteristics, mainly lift and drag, of wind turbine airfoils. The wind tunnel test will be conducted at incompressible conditions with Mach numbers below 0.2 and low Reynolds numbers in the order of 500,000 when using an active grid to generate turbulence and up to 1 Mio for passive grids. Turbulent flows with similar statistical properties as atmospheric turbulence are produced in the wind tunnel using an active grid. Based on the measurement data new models will be developed that account for the influence of turbulent inflow conditions on airfoil polars and their dynamics, respectively.

4.2 Wind tunnel description

4.2.1 Test section

The wind tunnel at the University of Oldenburg is a closed-loop facility (Göttingen-type) with a cross-section of 0.8m x 1m (H x W). It can be operated either with an open or with closed test section, but during the AVATAR project, only the closed test section will be used.
The closed test section has a length of 2.6m with airfoil segments being installed vertically at approximately 1.1m downstream the outlet. Devices for flow manipulation, like classic square grids, fractal grids or the active grid, can be mounted at the wind tunnel outlet to create turbulent flow conditions. The sidewalls and parts of the top and bottom plates are made of acrylic glass in order to permit optical access to the experiment.

4.2.2 Flow conditions

Wind velocities up to 50 m/s can be reached in the wind tunnel at a background turbulence intensity of about 0.3%. However, turbulence will be induced by means of an active grid in order to mimic atmospheric wind conditions. The active grid setup in Oldenburg consists of 16 horizontal and vertical axes with attached flaps. Each axis can be moved individually and thus, specific reproducible flow conditions can be achieved.

4.2.3 Instrumentation

The closed test section of the wind tunnel at the University of Oldenburg features 80 wall pressure sensors at the sidewalls. It is entirely accessible allowing for flow measurements using optical sensing techniques like Particle Image Velocimetry (PIV) and 2D-Laser-Doppler-Anemeometers (LDA) as well as conventional hot-wire sensors. The airfoil segments under investigation will be equipped with pressure taps along its chord. Additionally, the upper and lower mountings of the airfoil segment are instrumented with 3-component force balances and a torque sensor (pitching moment).

4.3 Test description

4.3.1 Measurements

During the test campaign, a baseline case of airfoil data without inflow turbulence will be measured including pressure polars, wall pressure distributions, lift and drag forces and torque. The measurements will also be carried out for different turbulent inflow conditions using passive grids followed by different motion patterns for the active grid.

4.3.2 Instrumentation techniques

A characterization of the turbulent inflow will be performed using hot-wire sensors and (if necessary) optical measurement techniques such as PIV or LDA. Lift and drag measurements of the airfoil will be obtained from the 3-component force balances located at the airfoil mountings.

4.3.3 Corrections

Standard corrections for laminar inflow conditions in closed test sections, such as wall corrections, will be applied.

4.3.4 Models

The decision about the profiles will be taken in accordance with the project partners

a. Suggested profiles: DU 00-W-212 or DU 91-W2-250
b. DU 91-W2-250 profile exists already and is equipped with 30 pressure taps
c. Both profiles are / will be made from aluminum with chord length 300mm
d. Manufacturing tolerances: ±0.05mm for 0-20% and ±0.1 for 20%-100% of chord from leading edge

4.3.5 Testing procedure

A typical range of angles of attack (-20° to +25°) will be covered by the experiments. Additional experiments at different angles of attack (e.g. 90° standstill case) can be performed for some cases if required. Given a chord length of 0.3m, the blockage will be about 10-13% for the regular range of angles, and 30% for the standstill case. At least three repetitions of each test case will be measured to check for the reproducibility of the obtained results.
Since the test matrix is still subject to discussion, no final test procedure has been determined yet. However, it is reasonable, to begin the wind tunnel tests with measurements of the baseline case without any turbulence before inducing turbulent flows with gradually increasing complexity using the active grid. This means in particular starting off with quasi-2D turbulence generated by moving only vertical grid axes and subsequently adding more intensity to the third flow component via the horizontal grid axes. Finally, full 3D turbulence with different statistical properties generated by active, fractal an classical grid will be examined.

4.3.6 Test matrix

A decision on the test cases for the turbulent flow conditions will be made according to prior agreement with the other project partners. Only a preliminary test matrix has been defined yet and is set for discussion among the partners.

max. Reynolds number	Airfoil	Grid	Turbulence characteristics	AOA	
Re <1,000,000	none	none	no turbulence	NA	BASELINE
Re <1,000,000	DU-xx-W-2xx	none	no turbulence	-20° to +25°	
Re < 500,000	none	active	2D, Gaussian	NA	ACTIVE
Re < 500,000	none	active	3D, Gaussian	NA	
Re < 500,000	none	active	2D, intermittent	NA	
Re < 500,000	none	active	3D, intermittent	NA	
Re < 500,000	DU-xx-W-2xx	active	2D, Gaussian	-20° to +25°	
Re < 500,000	DU-xx-W-2xx	active	3D, Gaussian	-20° to +25°	
Re < 500,000	DU-xx-W-2xx	active	2D, intermittent	-20° to +25°	
Re < 500,000	DU-xx-W-2xx	active	3D, intermittent	-20° to +25°	
Re < 1,000,000	none	classical	3D, Gaussian	NA	PASSIVE
Re < 1,000,000	DU-xx-W-2xx	classical	3D, Gaussian	-20° to +25°	
Re < 1,000,000	none	fractal	3D, intermittent	NA	
Re < 1,000,000	DU-xx-W-2xx	fractal	3D, intermittent	-20° to +25°	

4.3.7 Output data format

4.4 Test incidences

4.5 Time Schedule

The first measurements of the test campaign are estimated for the first quarter of 2015.

5. Moderate Reynolds and Mach Number test– DTU Wind tunnel test (Niels Sørensen)

5.1 Test objectives

The objective of the planned experiment is to test an airfoil suited for wind turbines with a good track record from other tunnels at a moderate Reynolds Number (up to ~8 mill), and a moderate Mach number (up to ~0.3) in a low turbulent environment (turbulence intensity ~0.1).
The objective is thus twofold, to gain new knowledge about airfoils at moderate Reynolds numbers, and secondly to validate the new National Wind Tunnel Facility in Denmark on a well proven airfoil. At the moment one airfoil candidate is the NACA 63-418 airfoil. Depending on the other tests and evaluations performed in the AVATAR project, the new findings will be considered when making the final decision about the airfoil and test setup.

5.2 Time Schedule

The tests are planned to be part of the initial validation of the new National Wind Tunnel Facility in Denmark, which at the moment are planned to be operational in the first half of 2015. The details about the planned tunnel are at the moment still confidential, but will be made available to the project partners as early as possible.

The details of the experiment are not fixed at the moment, but should be planned in detail early in 2015.