# Final report

## PUBLIC VERSION

# 1. Project details

| | |
|---|---|
| **Project title** | Participation to the IEA Task on Quiet Wind Turbine Technology |
| **File no.** | 64016-0056 |
| **Name of the funding scheme** | EUDP 2016 |
| **Project managing company / institution** | Danmarks Tekniske Universitet (DTU) |
| **CVR number** (central business register) | DK30060946 |
| **Project partners** | |
| **Submission date** | 27 November 2020 |

# 2. Summary

**English summary**

The aim of the project is the participation to the IEA Wind Technology Collaboration Programme - Task 39 entitled “Quiet Wind Turbine Technology”. The main technological activities within this Task concentrated on one side on two benchmarks involving several research institutes. It is expected that these collaborative efforts will continue in the future and possibly lead to scientific publications. On the other side, a number of dissemination activities were undertaken, both in the form of fact sheets, but also a broader impact publication and an overview document. The results of the project should benefit the participants in the shorter perspective, but also the whole wind turbine noise community through these disseminations and publications in the longer one. Ultimately, the work conducted in this project should contribute to the further integration of wind energy in the Danish and international energy supply, meeting new political goals of clean energy.

**Dansk resumé**

Målet med projektet er deltagelse i IEA Wind Technology Collaboration Programme - Task 39 med titlen "Quiet Wind Turbine Technology". De vigtigste teknologiske aktiviteter inden for denne opgave koncentrerede sig på den ene side om to benchmarks, der involverer flere forskningsinstitutter. Det forventes, at disse samarbejdsformer vil fortsætte i fremtiden og muligvis føre til videnskabelige publikationer. På den anden side blev der gennemført en række formidlingsaktiviteter, både i form af fakta-ark, men også en bredere publikationspublikation og et oversigtsdokument. Resultaterne af projektet skulle gavne deltagerne i det kortere perspektiv, men også hele vindmøllestøjsamfundet gennem disse formidlinger og publikationer i det længere. I sidste ende skal arbejdet i dette projekt bidrage til den yderligere integration af vindenergi i den danske og internationale energiforsyning og opfylde nye politiske mål for ren energi.

# 3. Project objectives

The objective of the project is the participation to the IEA Wind Technology Collaboration Programme. The latter aims at promoting international collaboration between research institutes, industry and other stakeholders in order to foster the development of wind energy. More specifically, the IEA Wind TCP is divided into Tasks and the present project is concerned with Task 39 entitled Quiet Wind Turbine Technology. In this perspective, the project did align with this objective and topic. The focus being on wind turbine noise and associated technologies, experts in the field convened in order to identify and address critical issues for the industry, in a technological and research context, through collaborative work.

Accordingly, the project has focused on relevant topics that the participants decided to address. In terms of technological developments, there have been two main activities related to benchmarking between participants. The first one is concerned with a wind turbine noise code benchmark. Its goal is to compare wind turbine noise simulation codes developed by different participants, using a reference turbine for the calculations. The project has shown that this is not an easy exercise and a number of difficulties have emerged, making the participants aware of the potential deficiencies of rotor noise models and their implementations, but also allowing for improvements when these problems are highlighted (see benchmark definition in Annex 6). The second one is a serration noise benchmark. In this case, the aim is to compare different wind tunnel measurements of aerodynamic noise from a reference airfoil equipped with a serration device. The goal is twofold: 1) compare wind tunnels and evaluate their differences and common aspects, and 2) advance knowledge about the aerodynamic and acoustic mechanisms associated to noise reduction from serrated trailing edges (see benchmark definition in Annex 7).

In parallel, a number of dissemination activities orientated toward a larger public have been undertaken. These are addressed later in this report (see Section 5).

# 4. Project implementation

The start of the project has been somehow disorganised because of a number of unexpected events. Following acceptance of the new IEA Wind Task 39 by the IEA Wind Executive Committee (end 2016), the initiator of the project TUD (Technical University of Dublin) announced that they could not lead the Task as Operating Agent (OA) due to a lack of internal funding and resources (March 2017). Subsequently, SEAI (Sustainable Energy Authority of Ireland) took over the lead as OA. But, after about 1 and 1/2 year SEAI also announced that they did not have the resources to lead this effort anymore (Nov. 2018). Then, DTU was offered, and did accept, to take over the role of OA in agreement with the other participants.

It is clear that the above management/OA difficulties have been detrimental to the implementation of the Task objectives during the beginning phase of the project. The two successive withdrawals of OAs from Ireland were definitely not expected, caused some uncertainties among the (including possible) Task 39 participants, and delayed the initiation of activities and collaborative work.

Another major difficulty with the present project can be attributed to the fact that, when the initial OA (TUD) initiated this new IEA Wind Task 39, the network of experts was not completely formed yet and the main activities were agreed upon between participants progressively in the course of the project.

In Nov. 2018, a new revised work programme was devised by the participants (see Annex 1), with a broader scope compared to the initial programme. The activities concentrated on a number of sub-tasks chosen in concertation with the participants. The initial work programme concentrated on Amplitude Modulation, and this topic was addressed at the beginning of the project. The new additional activities agreed upon after this initial phase are described below in more details.

# 5. Project results

The original objective was to conduct, as a first step, an exhaustive study on Amplitude Modulation of wind turbine noise, which should have been finalized with a guidelines document. Other research topics were not specified at the start, but it was expected that the participants would identify and address additional topics relevant for wind turbine noise technology along the way.

DTU in collaboration with a consulting company in the UK (ION Acoustics Ltd), and the support of SEAI, conducted a review on the topic of Amplitude Modulation (see Annex 2) which led to a Fact Sheet (see Annex 3). Nevertheless, this did not lead to the expected guidelines document. Note however that contacts and interactions between Task 39 and the IEC standard committee for wind turbine noise measurements (IEC 64100-11) have been established. The IEC is currently implementing an Annex to the standard for the measurements of Amplitude Modulation of wind turbine noise.

In addition to a number of dissemination works (see further), the main technological results revolve around two benchmark exercises: the wind turbine noise code benchmark and the serration benchmark. In the first one, a number of pitfalls for the implementation of airfoil models into a rotor noise codes were identified. Each participants could also, by comparing with other participants' results, improve their own models (see Annex 6). The study is on-going and it may be expected that new difficulties in the comparisons will arise, yielding to further findings related to wind turbine noise simulations. In the second one, measurements have been performed in DTU and Delft University acoustic wind tunnel facilities, and preliminary comparisons are being conducted (see Annex 7). Measurements were also performed in DLR wind tunnel facility a couple of weeks ago (at the time of writing). Hence, it is too early at this stage of the study to obtain firm results and conclusions.

IEA Wind TCP is a non-profit organization and the aim of the different Tasks is not commercial. However, the results of the project/Task should benefit the participants and participating countries, either by direct scientific and technological findings, or as dissemination as reported below.

The Task 39 activities were presented as oral presentations at two workshops during conferences: WindEurope 2018 Conference in Hamburg (Session: Solutions & facts on noise, health & public acceptance), and the WindEurope Conference & Exhibition 2019 in Bilbao (Session: Industry encounter on IEA Wind's research and activities).

The Task 39 activities were also presented at the Wind Turbine Noise conference as a poster (see Annex 4). In addition, an oral presentation was given at this same conference on one of the Task activities (the wind turbine noise code benchmark) with corresponding conference proceedings (see Annex 5).

There exist also a number of results that have not been published yet, but which will certainly lead to scientific journal articles or conference presentations. The first one stems from a collaborative work between DTU, DLR (Germany), Vestas (DK) and GE Renewable Energy (Germany). It summarizes future trends and needs from the industry regarding technologies related to wind turbine noise. The paper was invited for publication in the WIREs journal (Wiley Interdisciplinary Reviews, Energy and Environment). Submission is pending to authorization of publishing by GE management. The second one has not been initiated yet, but has been agreed upon. The so-called Serration Benchmark (see above) is a collaborative work between DTU (DK), DLR (GE), Delft University (The Netherlands) and it is planned to publish the results of this benchmark once the analysis of the results have been completed, i.e. in year 2021.

In addition to the Fact Sheet on Amplitude Modulation mentioned earlier (see Annex 3), another Fact Sheet dealing with the debated subject of Low-Frequency Noise from wind turbines is currently under review by international specialist in the field.

Finally, an important dissemination activity was also initiated in the early phase of the project. It is concerned with a review of international wind turbine noise regulations. The goal is to gather noise limit regulatory schemes related to wind turbines in an exhaustive number of jurisdictions worldwide (at least where such exists) in the form of a catalogue. From there, an analysis is conducted in order to classify the various choices and their specific practical implementations in policies. The document is still under development with various experts in the field contributing. It is believed that this document should provide guidance to decision-makers and/or politicians in countries that are in the phase of developing or increasing wind energy integration in their energy system, but facing inadequate noise regulations for this purpose.

# 6. Utilisation of project results

As the project is based on a collaborative work, the technological findings will primarily benefit the participants themselves. However, this also contributes to advances in terms of general scientific and technological knowledge in the concerned community, e.g. through dissemination in the form of publications individually as a consequence of the work conducted in the Task, or jointly in the context of the present IEA Wind Task 39.

Note that IEA Wind TCP is a non-profit organization, and commercialization is not expected as a direct result of the Tasks activities.

In other respects, public acceptance is a hindrance for the penetration of wind energy in the energy supply and market. Scientific and ultimately technological progresses in the domain of wind turbine noise understanding and reduction can have a positive effect on the public perception of noise (both physically and also in their attitude toward wind turbines), and thereby accelerate the energy policy objectives toward decarbonization through wind energy.

# 7. Project conclusion and perspective

Because of the relatively slow initiation phase of the IEA Wind Task 39, disrupted by a number of changes in leadership, it took some time to rally motivated participants. Nevertheless, after this initial phase, a number of topics related to wind turbine noise technology have been identified as important for the industry, in concertation with experts in the field both from the academic and industrial communities. A number of relevant sub-task activities have been established, and a number of participants are actively contributing to them.

The goal is now to pursue and consolidate these efforts, and it is believed that this will be the case as participants appear to appreciate the benefit that can be gained from such collaborations. As mentioned above, most of the activities are still on-going and require in most cases long time efforts to bear fruits. New activities need to be initiated in parallel in the future. During the last phase of the project (i.e. during the last year approximately), a number of countries and institutions have shown interest in the project. The Netherlands (with TNO and Delft University) have officially joined the Task 39. There is now active discussions with NREL about Task 39 activities (in fact, some collaborations have already been initiated, even if USA is not formally part of Task 39 yet), and USA (through NREL and the DOE) have shown interest in joining Task 39.

Although industrial partners are less active with their contributions to the activities themselves, it is clear that the work conducted within the Task 39 present some interest to them. Indeed, most of the large wind turbine manufacturers and other industrial stakeholders are represented during the regular (3-4 times a year) IEA Wind Task 39 general meetings, following up on the on-going activities and providing their inputs.

# 8. Appendices

- Annex 1: Revised Task 39 work programme, September 2018, Task 39 meeting (Page 7)
- Annex 2: Amplitude Modulation state-of-the-art report (P. 10)
- Annex 3: Amplitude Modulation fact sheet (P. 28)
- Annex 4: Poster, Task 39 Activities, Wind Turbine Noise conference 2018, Lisbon (P. 33)
- Annex 5: Conference proceedings, Wind Turbine Noise Code Benchmark, WTN conference 2018, Lisbon (P. 35)
- Annex 6: Definition of the Wind Turbine Noise Comparison Benchmark (P. 49)
- Annex 7: Definition of the Serration Benchmark (P. 65)

# ANNEX 1

# Revised IEA Task 39 Work Programme

| No | WP | Sub-WP | Remark | Milestone |
|---|---|---|---|---|
| **WP0** | **Management and coordination** | Technical management<br>Administrative management | Change of operating agent | |
| **WP1** | **Interdisciplinary Education and Guidance** | Table of contents for state of the art report on quiet wind turbine technology | | |
| | | Template for catalogue/database of national wind turbine noise regulations<br>Associated explanatory graphic(s)<br>Considerations when developing WTN guidance | To be provided as online resource | |
| | | Fact sheets - Key topics explained in as simple as possible language for regulators<br>• Amplitude Modulation<br>• Low Frequency noise<br>• Infrasound<br>• Tonal Noise<br>• Measurement technology<br>• Noise indices and measurement | | |
| | | Public Engagement on Noise<br>• Communicating noise concepts to the lay person<br>• Auralisation | (Task 28 collaboration) | |
| **WP2** | **Physics of Noise** | Noise modelling<br>• Benchmarking of noise models<br>• Propagation studies<br>• Farm level and wakes | (Collaboration with MEXNEXT)<br>(Collaboration with WAKEBENCH?) | |
| | | Quiet Wind Turbine Technologies<br>• Categories and classification – sources and pathways addressed<br>• Noise emission mitigation<br>• ?Optimisation? compromises e.g. soundscape manipulation/ customization, aerodynamic v.s tonal noise | | |
| | | Quantification/Qualification<br>• Consideration of physical effects & pathways - High Frequency Noise, Low Frequency Noise, Infrasound, Tonal Noise, vibration (& Vibration induced noise?)<br>• Field experiments (TREMAC, WEA Akzeptanz etc.<br>• Physical metrics<br>• Field measurements<br>• Data and findings from compliance monitoring<br>• Field experiments by practicing acousticians<br>• Results from field testing of Quiet Wind Turbine Technologies | | |
| **WP3** | **Psychology of Noise** – Psychoacoustics *(To be developed upon recruitment of* | Field-based psychoacoustic surveys<br>• Quantifying annoyance – survey instrument design | (Collaboration with Task 28) | |
| | | Laboratory based psychoacoustics | (subject to | |

| | | | | |
|---|---|---|---|---|
| | *participants)* | | participant) | |

## WP1 Interdisciplinary Education and Guidance

- Table of contents for state of the art report on quiet wind turbine technology
- Template for catalogue/database of national wind turbine noise regulations
  - Explanatory Graphics
  - Issues that need to be considered in developing WTN guidance
- Fact sheets- Key topics such as explained in as simple as possible language for regulators
  - AM
  - Low Frequency noise
  - Infrasound
  - Tonal Noise
  - Measurement technology
  - Noise indices and measurement
- Public Engagement on Noise
  - Communicating noise concepts to the lay person (Task 28 cooperation)
  - Auralisation

## WP2 Wind Turbine Noise and modelling

- Physics of Noise
  - Noise modelling
    - Benchmarking of noise models (Collaboration with MEXNEXT)
    - Propagation studies
    - Farm level and wakes (Collaboration with WAKEBENCH?)
  - Quiet Wind Turbine Technologies
    - Categories and classification – sources and pathways addressed
    - Noise emission mitigation
    - ?Optimisation? – compromises e.g. soundscape customizing aerodynamic v.s tonal noise
  - Quantification/Qualification
    - Consideration of physical effects & pathways - High Frequency Noise, Low Frequency Noise, Infrasound, Tonal Noise, vibration (& Vibration induced noise?)
    - Field experiments (TREMAC, WEA Akzeptanz etc.
      - Physical metrics
    - Field measurements
      - Data and findings from compliance monitoring
      - Field experiments by practicing acousticians
      - Results from field application of QWTT

## WP3 Psychology of Noise – Psychoacoustics (To be developed upon recruitment of participants)

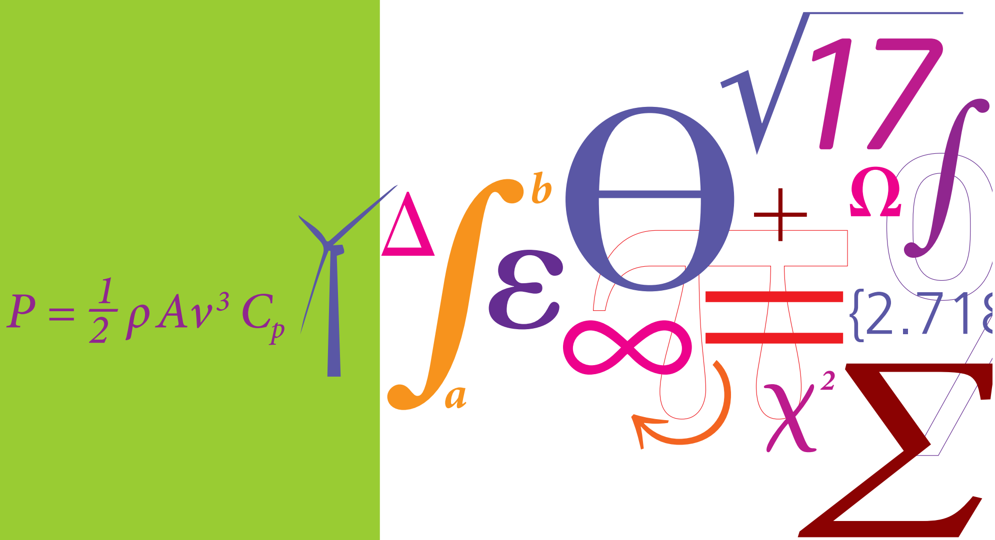
- Field-based psychoacoustic surveys (Collaboration with Task 28)
  - Quantifying annoyance – survey instrument design
- Laboratory based psychoacoustics ( subject to participant)

# ANNEX 2

# Amplitude Modulation of Wind Turbine Noise

## State of the Art Review

Report E-0***




Franck Bertagnolio
DTU Wind Energy
July 2018

**Amplitude Modulation of Wind Turbine Noise**

State of the Art Review
2018

Af
Franck Bertagnolio



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**Summary (max. 2000 characters):**
This report gives an overview of current knowledge and state of the art for issues related to the acoustic phenomena referred to as ‘amplitude modulation’ of wind turbine noise. The physical mechanisms generating amplitude modulation are highlighted. In the context of regulatory limits for wind turbine noise emissions, existing methods for evaluating and quantifying amplitude modulation through field noise measurements, as well as their practical implementations as legal noise constraints for wind turbines, are discussed.

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# Preface

It is a well-known fact that wind turbines produce noise. Noise intensity can vary in level and higher noise levels are naturally perceived as more annoying by potential dwellers living near wind turbines. Furthermore, changes in noise level are particularly noticeable and potentially even more annoying for humans (than for example a higher but constant noise level). Such changes in noise level are generically denoted as 'amplitude modulation'. However, it covers a large range of phenomena with different noise characteristics. This report provides an overview of the different physical mechanisms at play, how the associated noise characteristics can be evaluated, as well as legal aspects related to wind turbine noise regulations.

# Content

## Summary

This report gives an overview of current knowledge and state of the art for issues related to the acoustic phenomena referred to as 'amplitude modulation' of wind turbine noise. The physical mechanisms generating amplitude modulation are highlighted. In the context of regulatory limits for wind turbine noise emissions, existing methods for evaluating and quantifying amplitude modulation through field noise measurements, as well as their practical implementations as legal noise constraints for wind turbines, are discussed.

# 1 Introduction

The aim of this report is to provide overviews of:

1. the different physical aspects related to wind turbine noise amplitude modulation, and

2. the state of the art for evaluating wind turbine noise amplitude modulation for regulatory purposes.

The next section is dedicated to the description of wind turbine noise Amplitude Modulation (AM). The third section provides a brief summary of the methods that have been proposed in the recent years to systematically quantify AM. The fourth section concentrates on regulatory issues and how noise limits on AM may be implemented in the future.

# 2 Physical Mechanisms Associated to Amplitude Modulation

In this section, the physical phenomena that may yield AM are reviewed. In the first section, a few facts about wind turbine noise are reminded in order to help the reader to understand in which context AM should be considered.

## 2.1 Standard Evaluation of Wind Turbine Noise

According to the IEC 61400-11 international standard for wind turbine noise measurements [1], wind turbine noise is evaluated by using 10 seconds time-series of acoustic pressure fluctuations recorded by a microphone located near the turbine. These time-series are converted to a single numerical value denoted as Sound Pressure Level (SPL) measured in decibels (db). SPL is a quantitative measure of the overall wind turbine noise level irrespectively of the noise qualitative characteristics, e.g. such as its frequency content. Note here that, as an intermediate step to calculate the SPL according to the standard, the measured noise spectra are A-weighted. A-weighting is in fact a filtering of the recorded noise to reflect the range of audible frequencies for humans (typically from 20 Hz to 20 kHz with a peak of sensitivity for the human ear in the 2–5 kHz range). Thereby, it provides a measure of noise more adapted to the human perception of noise. A-weithed SPL are measured in db(A).

In brief, the standard specifies that these SPL(A) values must be binned/sorted according to the mean wind speed simultaneously measured near the wind turbine. For being valid, each bin must contain at least 10 occurences of valid noise measurements at each specific wind speed. Then, the SPLs in each bin are averaged together to provide the noise characteristics of a given wind turbine as a function of wind speed.

The above is illustrated for a standard pitch-regulated 2 MW wind turbine in Fig. 1. It shows how wind turbine noise increases with wind speed in conjunction with the power until rated wind speed is reached (here around 15 m/s). Above rated wind speed, the SPL keeps constant, similarly to the power output, as a consequence of the constant rotor rotational speed enforced by the wind turbine controller in this region of the operational range, which is characteristic for modern pitch-regulated turbines.

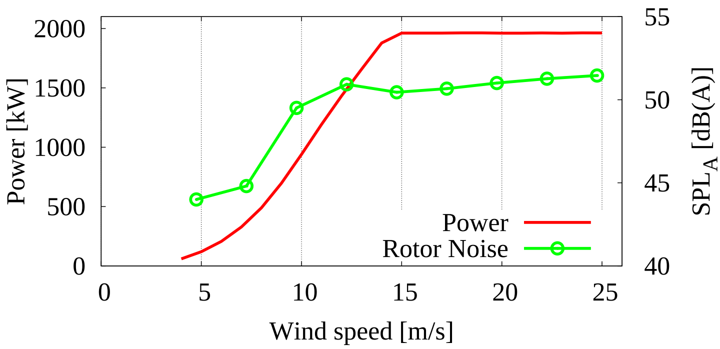


Figure 1: A-weighted Sound Pressure Level and power output of a standard 2 MW wind turbine as a function of wind speed.

However, various unsteady effects with time scales shorter or longer than the 10 seconds of the recordings (see above) may occur for an operating wind turbine. They translate as temporal variations of the noise level, but these unsteady features are averaged out when evaluating noise using the above procedure. These noise level variations are generically denoted as ‘amplitude modulation’, however this terminology includes various physical phenomena as described below.

## 2.2 Wind Turbine Noise Intermittency

A typical unsteady feature of wind turbine operation is the varying wind speed due to the stochastic nature of the atmospheric flow. Consider a wind turbine with the noise characteristics as displayed in Fig. 1. Assuming that the wind speed is relatively low, say 5 to 6 m/s, and that the wind speed increases up to 8 m/s or more within a time period of the order of, say 10 to 30 s, then a listener would experience a noise level increase of more than 5 dB(A) during this period. This would be a clearly noticeable auditive event. There exist strong evidences that such intermittent noise levels are more disturbing and potentially annoying than a similar noise source with constant amplitude/level [2, 3, 4].

Nevertheless, such long time scales (of the order of 10 s or more) are not considered directly as 'amplitude modulation' in the wind energy community, but more as intermittent noise. Furthermore, these noise level intermittencies appear not to be the focus for emerging legislations on wind turbine noise AM. Therefore, these are not further considered in the remaining of this document.

## 2.3 Wind Turbine Noise Swish

Another occurence for noise level temporal fluctuations originates from the rotation of the blades and is sometimes subjectively described as 'swish'. Indeed, anyone who has been standing next to a wind turbine has experienced the obvious periodic fluctuation of the noise created by the passage of each blade, therefore with a time periodicity of the order of one to a couple of seconds for large-size turbines. Several mechanisms may be contributing to this swish, possibly reinforcing or working against each other. Two of these are reported below.

As the blades rotate, they are moving up and down across the atmospheric boundary layer which is characterized by a wind speed gradient from low velocity near the ground to high velocity at the top of the turbine (i.e. for a blade pointing upward, see Fig. 2). From basic knowledge of the velocity triangle for a wind turbine airfoil section, it can be easily conclude that this periodic wind speed experienced by each blade does yield a periodic variation of the angle of attack impinging on them. As far as trailing edge noise is concerned (as it is typically the most audible noise source from a wind turbine), this temporal variation of the angle of attack will periodically alter the frequency content of the emitted noise and its perception. These varying noise frequency characteristics can easily be interpreted, at least to the human ear, as AM, even though it does not necessarily imply that the actual overall noise energy content is modified when integrating the sound pressure levels over the whole spectral range.

The second classical AM mechanism is originating from noise directivity patterns. Consider again only trailing edge noise and its cardiod directivity pattern characterized by a highest noise emission direction pointing toward the leading edge of the airfoil/blade [5]. It is clear that a person located in the rotor plane (i.e. crosswind) will hear prominently each one of the rotor blades approaching toward him/her in sequence while the receding blades will be more silent. This will also be experienced as amplitude modulated noise, or swish. Nonetheless, a person located directly downwind or upwind of a turbine may also experience this swish although to a much lesser extent,

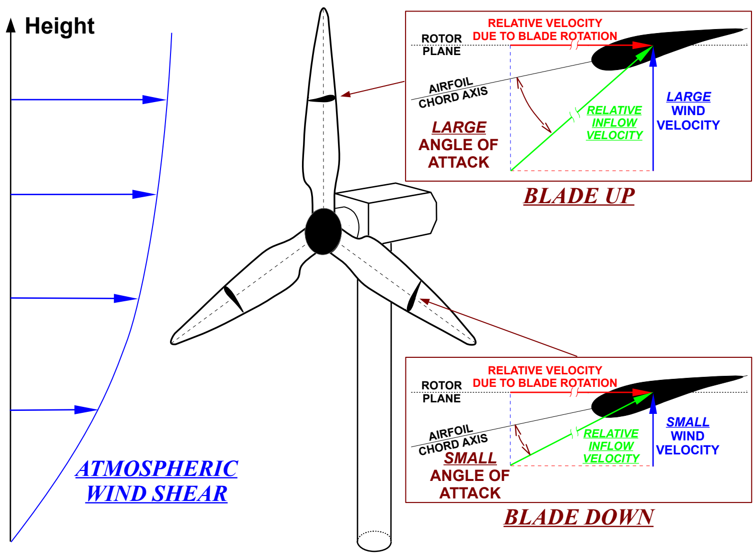


Figure 2: Sketch illustrating the varying angle of attack of the relative velocity impinging a blade section as it rotates within the atmospheric wind shear.

as illustrated in Fig. 3. The expected lower AM stems from the facts that the noise directivity pattern is roughly symmetric relatively to the airfoil chord and that the listener is always facing the same blades' face as these rotate. Therefore, the changes of noise levels in term of directivity are expected to remain fairly low. However, directivity patterns are complicated and three-dimensional geometrical patterns can also play a role. Furthermore, the blade sections along the span are not exactly aligned with the rotor plane which may again create periodic fluctuations of the perceived noise depending on the listener position relatively to the rotor disk.

## 2.4 Other Amplitude Modulation Mechanisms

Although the mechanisms described in the previous section are considered as the most probable and accepted explanations for AM occurences (sometimes referred to as Normal AM), other mechanisms may produce AM. These are referred to as OAM or sometime as Excessive (Enhanced) Amplitude Modulation (EAM).

Stall noise has been often mentioned as a source of OAM. Indeed, as the blade rotate up and down in the atmospheric boundary layer with larger wind speed at higher

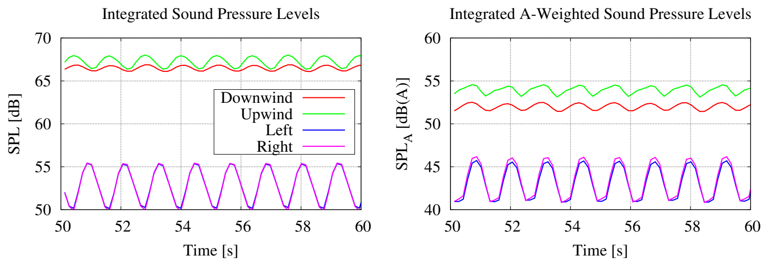


Figure 3: Time-series of integrated SPL showing amplitude modulation due to blades' rotation and directivity effects illustrated by four listeners' locations relatively to the wind turbine (Left: sound pressure levels, Right: A-weighted sound pressure levels).

altitude generating swish as explained in the previous section, extreme wind shears may yield large angles of attack when the blade is pointing upward, possibly triggering stall and thereby stall noise. The sudden occurence of stall, followed by reattachement of the flow when the blade rotates downward toward lower wind speed, may produce large changes in noise levels and/or their frequency content, which is akin to the classical AM described above, but possibly more perceptible. Similar occurence of stall may be caused by non-optimal operation of the rotor such as when the turbine operates with a yaw error or because of an atmospheric wind veer.

A somewhat similar scenario was proven to occur on wind turbines during a measurement campaign [6], although noise was not measured directly in this particular campaign. The phenomenon occurs when the average wind speed is low. Then, the turbine operates at constant pitch but variable rotational speed below rated power as it is normally the case for most pitch-regulated turbines. When a wind gust or a rapid increase of the average wind speed does occur, the wind turbine controller will allow the rotational speed of the rotor to increase in order to maximize the power output. However, due to the inertia of the rotor itself, it cannot reach this optimal rotational speed immediatly and there exists a time delay between its original rotational speed and the optimal one. Therefore, during this period of time the turbine will operate in conditions for which it is not designed for, and which in fact may produce stall of the flow on parts of the blades, and thereby again stall noise.

Finally, atmospheric conditions have been suspected to also play a role on AM. Indeed, the propagation of noise in the atmosphere is largely affected by velocity and temperature vertical gradients bending the trajectory of acoustic sound waves [7]. Sound wave trajectories are typically bended upward when travelling upwind (and downward when travelling downwind), possibly creating a shadow zone upwind of the turbine (see Fig. 4). A possible scenario could be that of a listener being alternatively in and out of the shadow zone of the wind turbine (here considered as the noise source) as a result of atmospheric turbulence randomly disturbing the paths of the sound waves.

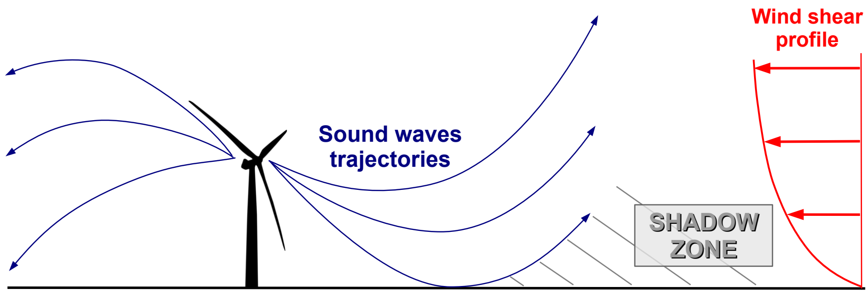


Figure 4: Shadow zone for the noise produced by a wind turbine.

# 3 Methods for Quantifying Amplitude Modulation

In this section, methods for quantifying AM are reviewed. The present report does not intend to provide an exhaustive list of all existing methods. For this, the reader is referred to the following report [8] (Work Package 5A). Here, the methods are shortly describes and a number of facts regarding assessing AM are considered.

## 3.1 Existing Methods

Over the last decade, a large variety of methods have been proposed in order to provide a reliable metric to assess AM. They all attempt to quantify, in one way or another, the peak to trough amplitude of the time-series of the SPL, or in other words the noise modulation depth. The SPL time-series must be evaluated with a sufficient sampling rate in order to accurately capture the peak to trough of the SPL time-series. It appears that a sampling rate of the order of 100 ms seems to be the consensus among the wind turbine noise community. AM can then be evaluated by defining a measure of the peak to trough values, or by further Fourier transforming the SPL time-series themselves for analysing the resulting frequency peaks.

In the recent years, two methods appear to emerge in the scientific community as the most popular candidates for practical application of wind turbine AM assessment:

the so-called Fukushima method [9] and RUK/IOA method [10].

### 3.2 Advantages and Pitfalls

Eventually, the intent of developing a wind turbine noise AM assessment method as defined above is to provide a tool for wind farm planner to design wind farms, and for the authorities to certify the compliance of a wind farm to wind turbine noise regulations. Therefore, such methods would be very useful for wind farm deployment in the future if and when AM become an additional constraint for noise regulations. Nevertheless, precisely because such methods would be used in the real world for projects which costs are usually quite high, if not very expensive, they should fulfill a number of criteria so that they can be sensibly used and to good effect.

A first important attribute is the fact that the method is an accurate measurement tool, in the sense that it should reflect a level of potential annoyance for the wind farm neighbours. Therefore, it is important that they are connected to psycho-acoustic analysis of human response to AM and the associated subjective annoyance ratings (see e.g. [11], Work Package B(2)).

Wind turbine noise measurements in the field are notoriously quite tricky, mostly because of background noise that can generally not be distinguished from wind turbine noise in an automated procedure (unless if the person analyzing the data comes back to the original audio recordings and listen himself to sort out corrupted audio samples, which can be quite time-demanding). However, an AM assessment method should be reliable enough, or at least provide a degree of reliability for the measurement values provided by the method. For example, a critical problem of existing methods is their potential to generate so-called 'false positive', i.e. high AM metric levels when there is actually none or little AM from the wind turbine(s) but the assessment procedure picks up and wrongly interprets background noise (e.g. cars passing by or bird chirping). Conversely, background noise or other disturbing factors could mask AM and provoke no significant quantitative response from the method when AM is actually present and clearly audible for a human.

Finally, the method should be relatively simple and straightforward to implement so that it can be used without being prone to a lot of mistakes.

## 4 Regulatory Issues

Once a metric for quantifying AM has been defined, it can be used as part of a noise limit regulation for the approval and certification of wind turbines and/or wind farms. To this date, and as far as the author is aware of, such noise limit regulations including

AM have only been used in the UK for a few sites. Note however that the controversy about AM has essentially brought all onshore wind farm projects in the UK to a standstill over the last few years. It seems that this situation will perdure until a clear set of rules for AM noise limits is in place.

As far as wind farm/turbine certification is concerned, the way a AM metric may be implemented can be divised in 4 main categories [8]:

- Use the AM metric value and add it as a penalty to the overall noise limit
- Identify a trigger value for the AM metric above which action must be taken
- Use the AM metric value, but do not specify how this should be used
- Use the AM metric value, but refer to context and/or human judgement to legislate

# 5 Conclusions

In this report, a review of the state of the art of amplitude modulation for wind turbine noise is provided. This report is by no means an exhaustive review of the state of the art, but intends to summarize important points about current knowledge and trends. For more details, the reader is referred to various more complete research and review studies recently conducted in the UK [11, 8, 10, 12] where the wind turbine noise community is actively working on the subject because of an intense debate concerning wind turbine noise AM undergoing there.

# Acknowledgments

This work was supported by Energistyrelsen (the Danish Energy Agency) as part of the EUDP (Energy Technology Development and Demonstration Program) project Jr. nr. 64016-0056 which grants the participation of Denmark to the IEA Wind - Task 39: Quiet Wind Turbine Technology.

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DTU Wind Energy is a department of the Technical University of Denmark with a unique integration of research, education, innovation and public/private sector consulting in the field of wind energy. Our activities develop new opportunities and technology for the global and Danish exploitation of wind energy. Research focuses on key technical-scientific fields, which are central for the development, innovation and use of wind energy and provides the basis for advanced education at the education.

We have more than 230 staff members of which approximately 60 are PhD students. Research is conducted within 9 research programmes organized into three main topics: Wind energy systems, Wind turbine technology and Basics for wind energy.


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# ANNEX 3

Task 39 Fact Sheet

# AMPLITUDE MODULATION IN WIND TURBINE NOISE

## Task 39: Quiet Wind Turbine Technology

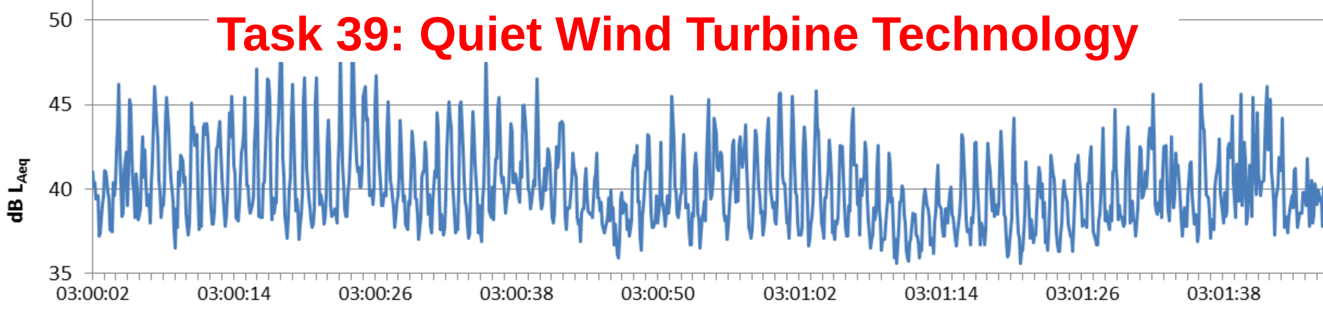


Figure 1. Measured Amplitude Modulation

**Wind turbines produce sound which can be modulated. In other words, the sound level is not constant. The modulation is often periodic and related to the blade passing frequency (Figure 1). The characteristic might be described by a listener as a regular 'swish', 'whoomph' or 'thump'. This modulation will stand out from the underlying background sound, and is therefore potentially more annoying than a sound of similar, but relatively constant level. This fact sheet presents the current state of knowledge and discusses control measures and mitigation.**

## General considerations

According to International Standard IEC 61400-11 [1], wind turbine sound is evaluated in 10-second averages from a microphone located on the ground near the turbine. Multiple recordings are made, and averaged together within wind speed bins, so as to cover the whole operational wind speed range of the turbine. This yields a sound output characteristic, an example of which is displayed in Figure 2. The values are stated in terms of A-weighted, sound pressure values. That is, a frequency weighting filter is applied so that the measured values are representative of the sensitivity of human ear.

However, various unsteady effects may occur with time scales shorter or longer than 10 seconds. These translate as temporal variations of the sound levels. Such unsteady features may not be present at the IEC measurement position and are, in any case, averaged out when evaluating wind turbine sound levels. However at residential distances there is strong evidence that amplitude modulation is more annoying than sounds with a constant level [2, 3, 4].

Although phenomena with different time scales may occur, Amplitude Modulation (AM) is usually defined as a fluctuation in sound level with a period corresponding to the blade passing frequency. For a large three-bladed turbine this is usually just less than once per second.

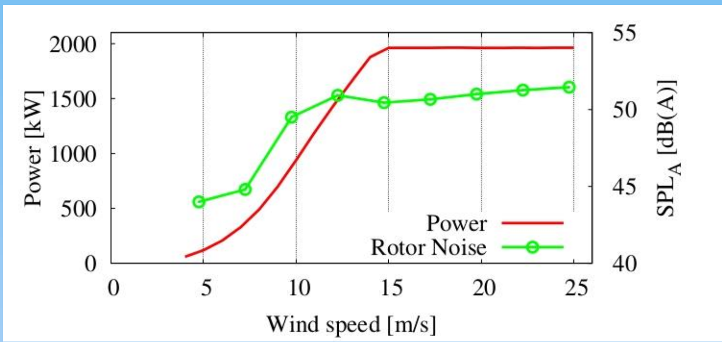


Figure 2. A-weighted Sound Pressure Level and power output of a typical 2 MW wind turbine as a function of wind speed

## Wind turbine noise "Swish" - AM

Anyone standing close to a wind turbine will experience the obvious periodic variation in the sound as each blade turns. Several mechanisms may be contributing to this AM. Two of these are discussed below.

### 1. AM due to trailing edge noise directivity

The most important feature of wind turbine noise is trailing edge noise. It has a cardioid directivity pattern characterized by a highest noise emission direction pointing toward the leading edge of the aerofoil/blade [5]. Therefore a person located nearby in the extended rotor plane (i.e. crosswind) will hear prominently each blade approaching toward them in sequence while the receding blades will be quieter. This will also be experienced as amplitude modulation, often described as 'swish'.

Nonetheless, a person located directly downwind or upwind of a turbine may also experience this swish although to a lesser extent, as illustrated in Figure 3.

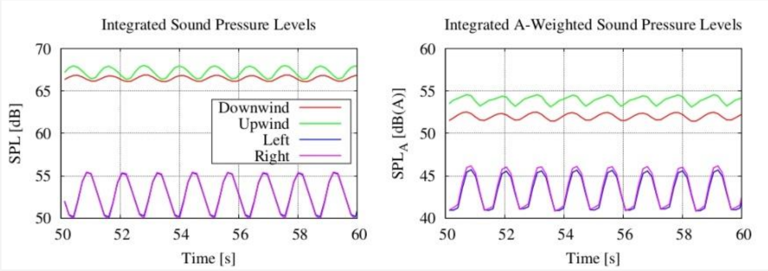


Figure 3. Time-series of integrated SPL showing amplitude modulation due to rotation of the blades and directivity effects illustrated by four listeners' locations relative to the wind turbine (Left: sound pressure levels, Right: A-weighted sound pressure levels)

The expected lower AM stems from the facts that the noise directivity pattern is roughly symmetric relatively to the aerofoil chord and that the listener is always facing the same side of the blades as these rotate. Therefore, the changes of noise level in terms of directivity are expected to remain fairly low. Nonetheless, directivity patterns are complicated and the blade sections along the span are not exactly aligned with the rotor plane such that AM can be observed depending on the listener position relative to the rotor disk.

## 2. AM due to wind shear

As the blades rotate, they are moving up and down across the atmospheric boundary layer which is characterized by a wind speed gradient from low velocity near the ground to high velocity at blade tip (i.e. for a blade pointing upward, see Figure 4). From knowledge of the velocity triangle for a wind turbine aerofoil section, the periodic variation in wind speed experienced by each blade results in a periodic variation of the angle of attack for the same blade pitch.

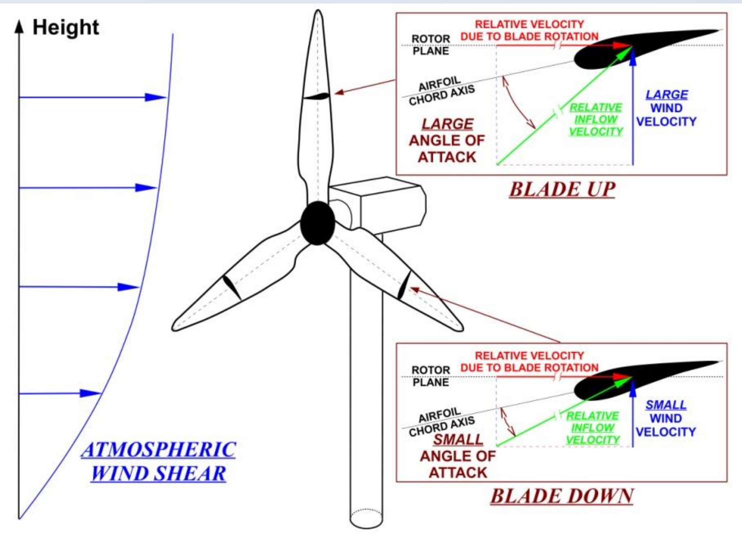


Figure 4. Sketch illustrating the varying angle of attack of the relative velocity impinging on a blade section as it rotates within the atmospheric wind shear

This temporal variation of the angle of attack will periodically alter the frequency content of the emitted noise and its perception. These varying frequency characteristics can be interpreted as AM by human ear, even though it does not necessarily imply that the actual overall noise energy content is modified when integrating the sound pressure levels over the whole spectral range. See Figure 5.

## Other Amplitude Modulation mechanisms

The two mechanisms described in the previous sections are considered to be known and accepted explanations for AM. However other mechanisms may produce AM.

Stall noise, or partial stall from flow separation has been often mentioned as a source of AM. High wind shear values can occur in stable atmospheric conditions and this may yield large angles of attack when the blade is pointing upward, possibly sufficient to trigger temporary stall and increased noise. Such noise is characterized by an increased low frequency content. Stable atmospheric conditions often occur during the hours of darkness when there is less turbulence and wind shear gradients tend to be higher. Flat landscapes also tend to have higher wind shear gradients and the highest values of AM as measured from peak to trough have been found to occur in flat landscapes at night.

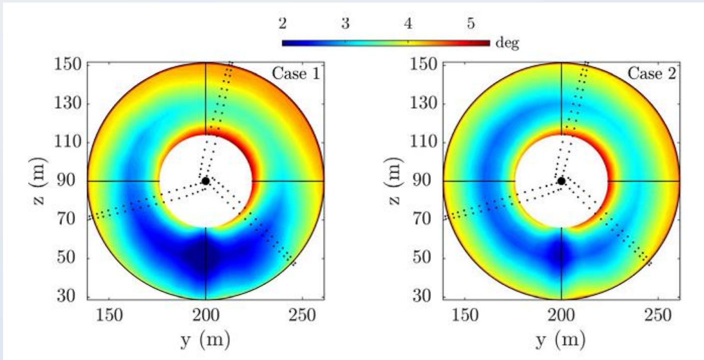


Figure 5. Time-averaged angle of attack across the rotor plane with the same hub height wind speed for two wind shear examples: high shear left and low shear right. See Reference 6.

However AM has also been found to occur on sites where the turbines were located on the downwind side of a hill such that the lowest point of the rotor was sheltered from the wind when it was blowing in a particular direction, but the upper sections remained exposed. Again this resulted in high wind shear conditions.

Similar occurrences of near stall conditions may be caused by non-optimal operation of the rotor such as when the turbine operates with a yaw error or because of an atmospheric wind veer.

A somewhat similar scenario was found to occur during a measurement campaign [7] when the average wind speed was relatively low. In such conditions, a turbine typically operates at constant pitch but with a variable rotational speed below rated power. When a wind gust or a rapid increase of the average wind speed occurs, the wind turbine controller will allow the rotational speed of the rotor to increase in order to maximize the power output. However, due to the inertia of the rotor itself, it cannot reach this optimal rotational speed immediately and there exists a time delay between its original rotational speed and the optimal one. For this period of time, the turbine will operate in conditions for which it is not designed, and which in fact may produce transient stall of the flow on parts of the blades, and thereby again produce stall noise.

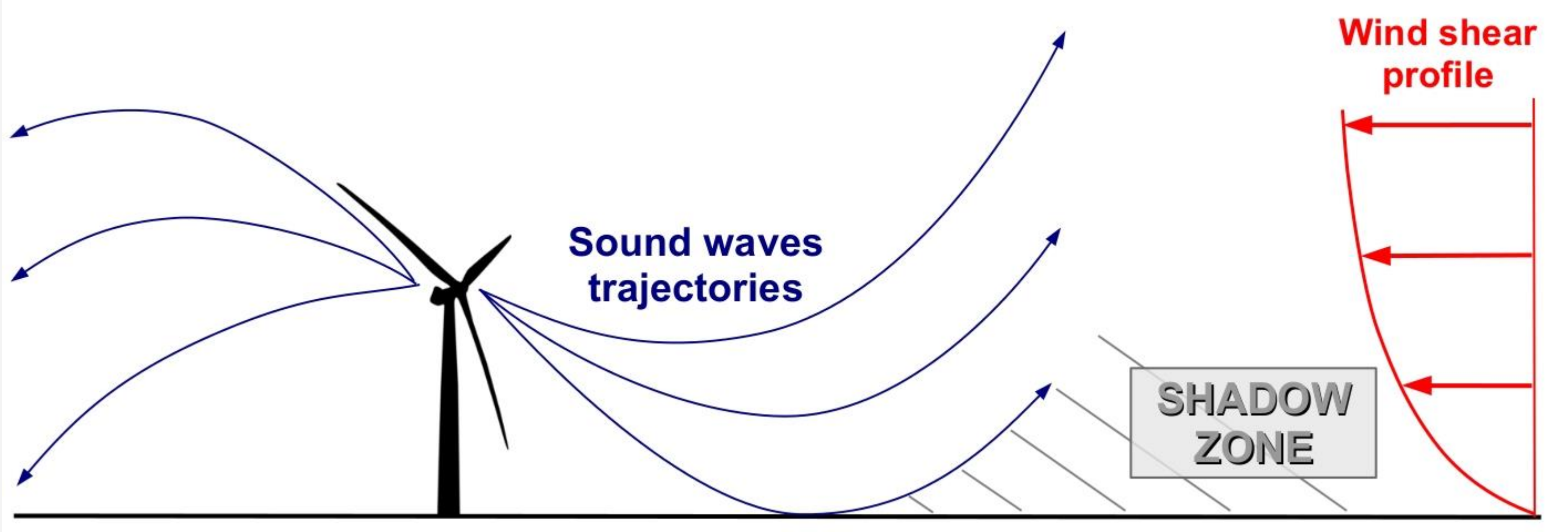


Figure 6. Shadow zone for the noise produced by a wind turbine

Finally, atmospheric conditions have been suspected to also play a role in creating AM. Indeed, the propagation of noise in the atmosphere is largely affected by velocity and temperature vertical gradients bending the trajectory of acoustic sound waves [8]. Sound wave trajectories are typically bent upward when travelling upwind (and downward when travelling downwind), see Figure 6. Variations in the trajectories will cause variable noise levels. Inflow turbulence and wake effects can also cause variations in sound level and AM. These issues were modelled in Reference 6.

## Methods for Rating AM

Over the last decade, a large variety of methods have been proposed in order to provide a reliable metric to assess AM. They all attempt to quantify, the peak to trough amplitude of the sound level time-series, or in other words, the modulation depth. However the modulation depth can also vary from each successive peak and trough and a simple visual assessment is not sufficiently robust for use in regulatory control.

In the first instance, the sound pressure values in the time-series must be evaluated with a sufficient sampling rate in order to accurately capture the peak to trough of the AM. It appears that a sampling rate of the order of 100 ms seems to be the consensus among the wind turbine noise community. From here, AM can then be evaluated by defining a measure of the peak to trough values, or further by carrying out a Fourier transformation of the time-series to determine the resulting peaks which correspond to the blade passage frequency and its harmonics. The advantage of the Fourier transform technique is that periodic AM can be evaluated and other transient or non-periodic noise can be excluded.

In recent years, two methods have emerged in the scientific community as the most popular candidates for practical application of wind turbine AM assessment: the so-called Fukushima method [9] and IOA method [10] which was an enhancement of a method proposed by Renewable UK [11]. The IOA Method can be used to process large data sets as it is efficient at identifying periods of AM and excluding spurious data such that relatively little manual inspection of the data is required. See Figure 7.

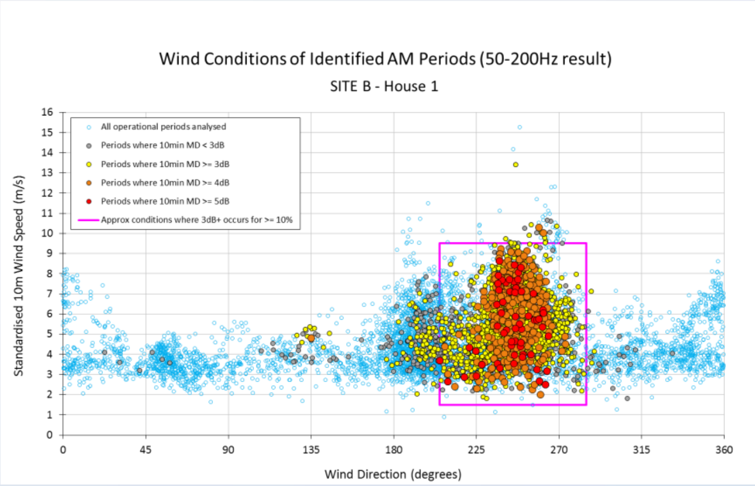


Figure 7. Analysis of site data from Reference 12

## Subjective Response

A first important attribute for any rating system is that it should reflect the potential annoyance for the wind farm neighbours. Therefore, it is important that it is connected to psycho-acoustic analysis of human response to AM and the associated subjective annoyance ratings. Various studies have been carried out as discussed in Reference [13].

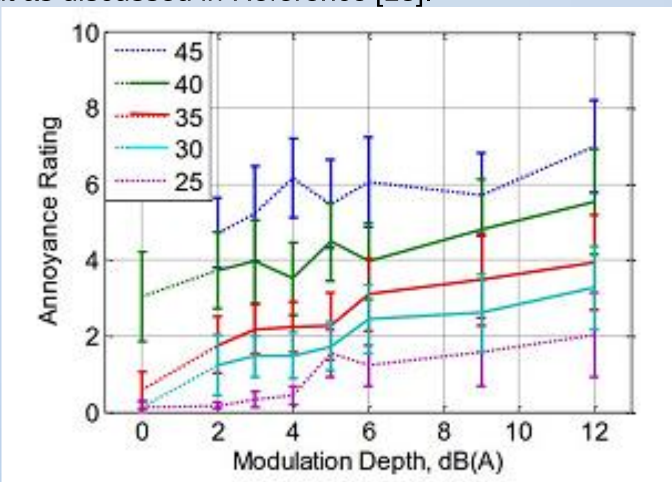


Figure 8. Relationship between modulation depth and annoyance rating with overall average level ($L_{Aeq}$) as a parameter. From von Hünerbein et. al. Reference 11 WP 2(B)

Such relationships could be used to construct a numerical penalty to be added to the measured sound levels where amplitude modulation is present. The proposed penalty from Ref. 13 is shown in Figure 9.

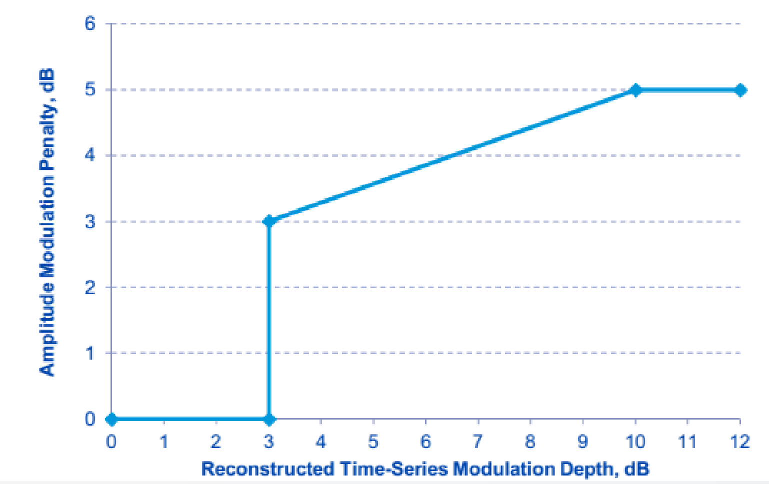


Figure 9. Example Penalty Scheme from Reference 13. This uses the IOA rating method as the modulation depth.

The penalty curve above is only one example and there is some debate regarding the actual values since it is possible to derive other curves. Furthermore, it must also be agreed how any control measures would work. There could be several ways that a planning limit could be applied:

- Use the AM metric value and add it as a penalty to the overall noise limit – this is what is done for tonal values for example in ISO 1996-2.
- Identify a trigger value for the AM metric above which action must be taken, irrespective of the overall level.

## Mitigation

At present, the development of AM rating systems and penalties can allow AM to be controlled at the planning stage. However there is no known method for predicting whether and when AM will occur at the development stage, although it is possible to state that AM under downwind conditions in flat landscapes at night is often experienced and therefore might require special consideration.

Where AM has occurred previously, mitigation measures have successfully been employed. Such measure have usually involved either:

- Modifications to pitch control mechanisms or;
- Modifications to the blades.

Results of such modifications are presented in [14].

Another possible development which is being investigated is to use cyclic pitch control to adjust the pitch of the blades during each revolution of the rotor. This is likely to reduce transient stall but will increase wear on the pitch control motors.

## More information

This Fact Sheet draws from the work of IEA Wind Task 39, a research collaboration among various countries. Its goal is to promote contacts between international experts in order to exchange learning, identify and report best practices in the measurement and assessment of noise, and develop an IEA Wind Recommended Practice contributing to the ongoing development of IEC standards for wind turbine noise.

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See our website at
www.ieawind.org/task_39.html#

# ANNEX 4

# IEA WIND TCP Task 39 – Quiet Wind Turbine Technology

*Operating Agent:* Franck BERTAGNOLIO, DTU Wind Energy

## OBJECTIVES

The International Energy Agency Wind Technology Collaboration Programme (IEA Wind TCP) is an international co-operation that shares information and research activities to advance wind energy research, development and deployment in member countries. It is divided into several groups of core activities named Tasks. As such, Task 39 – Quiet Wind Turbine Technology aims at coordinating international research on quiet wind turbine technology and in related technology fields. Technology to be considered within this Task is not solely wind turbine technology but also related technology and practices, that may facilitate its deployment, in related fields including acoustics and noise regulations.

# ON-GOING ACTIVITIES

## WIND TURBINE NOISE CODE BENCHMARK


The aim of this benchmark is to compare and validate Wind Turbine Noise Simulation codes. Indeed, while manufacturers and research institutes use a variety of models, there is no recognized simulation tool on the market. This exercise will give an overview of the current state of the art for such existing tools. The focus is set on aerodynamic noise. Mechanical noise and sound propagation are left out from this study. As a result, it is paramount that the codes are based on identical correct input data for the turbine aerodynamics. This benchmark is therefore highly linked to a similar exercise as part of IEA Wind Task 29 for wind turbine aerodynamics. The reference turbine is the NM80 2.3MW turbine which was studied during the DANAERO project. The measurements are used for verification of the aerodynamic input data. High-frequency surface pressure measurements can be used to confront the models with experimental data.

## SERRATION SIMULATION CODE BENCHMARK

The aim of this benchmark exercise is to create a high-quality and publicly available wind tunnel data set for noise measurements on an aerofoil with serrated trailing edge and benchmark the existing noise prediction codes. The wind tunnel data should help to improve the noise prediction. The experimental data will be acquired in the new Poul La Cour wind tunnel (DTU Wind Energy, DK).

## PUBLICATIONS (Fact sheets, Wind Turbine Noise Regulation Catalogue, etc)

One of the objectives of the IEA Wind TCP is to foster the further development and deployment of wind energy. In this respect, it is also its goal to inform the public about technical, regulatory and societal aspects related to wind energy. Wind turbine noise raises important environmental concern among the public (mainly in the form of annoyance) and Task 39 is dedicated to shed light on these issues in an objective way. For this, so-called "fact sheets" are published providing information on various topics in a form that is easily accessible to a large audience, not necessarily specialized on the technicalities of wind turbine noise.


# PLANS FOR FUTURE ACTIVITIES

Current participants to Task 39 have identified a number of topics that are considered as most relevant. They are divided into 3 main categories: 1) Interdisciplinary, Education & Guidance 2) Physics of Noise 3) Psychology of Noise. Fact sheets and publications are part of the first one. A review of Wind Turbine Noise Regulation worldwide is in progress. The benchmarks can be considered as part of the second. A future benchmark on noise propagation is anticipated. So far, the third category is not active but is connected to activities on annoyance in IEA Wind Task 28. We are looking for participants to activate the various topics and/or suggest new ones. If you would like to collaborate with other countries on a specific subject, please contact the Operating Agent (below) to be informed about the opportunities that Task 39 can offer.

# CONTACTS

*Main Contact- Operating Agent*: Franck Bertagnolio (frba@dtu.dk)

*Wind Turbine Noise Code Benchmark*: Franck Bertagnolio (frba@dtu.dk)

*Serration Simulation Code Benchmark*: Andreas Fischer (asfi@dtu.dk)

*TASK 39 website*: https://community.ieawind.org/task39/home

# ANNEX 5

8th International Conference
on
Wind Turbine Noise
Lisbon – 12th to 14th June 2019

# A Wind Turbine Noise Code Benchmark - Round 1

**Franck Bertagnolio**
**DTU Wind Energy, Roskilde, DK-4000, Denmark**

**Second C. Author**
**Institution, City, Province, Zip Code, Country**

## Summary

The aim of this study is to compare and validate wind turbine noise prediction codes from various institutes and companies. This effort is part of the IEA Wind TCP Task 29 (Wind Turbine Aerodynamics) and IEA Wind TCP Task 39 (Quiet Wind Turbine Technology). The benchmark is divided into 3 rounds which will be dealt with incrementally in time, and the focus of the present article is on the first round. Note that this study concentrates on aerodynamic noise generation, therefore mechanical noise and long-range atmospheric propagation effects are not considered.

## 1. Introduction

Wind turbine noise emissions are commonly measured in the field according to the IEC-64100-11 standard [4]. Microphones are placed on the ground downstream of the turbine at a specified distance from the tower (equal to the height of the tower plus half of the rotor diameter). The wind turbine is considered as a monopole noise source and is thereby supposed to emit the same noise levels in all directions. Thus, the mesured sound pressure levels can be related to the sound power levels of the turbine. Immission levels at dwellings can be evaluated using a variety of methods predicting the propagation losses, from simple semi-empirical formulas to advanced simulation methods such as Parabolic Equations or Computational Aero-Acoustics. Furthermore, the results of the above standardized measurements are binned according to the wind speed to reflect the actual variations of the noise emission levels with respect to the wind conditions. Modern turbines produce typically less noise at low wind speed because of the lower rotational speed, and nearly constant noise above rated power when the rotational speed is normally kept fixed and power is regulated by the controller through the blade pitch.

However, as far as the actual noise emissions are concerned (i.e. when considering the wind turbine as the source of noise), the physics of noise generation mechanisms is more complicated than the above conceptualization. The assumption of a monopole noise source is certainly a first order approximation. Nevertheless, note that for wind turbine certification it is considered as satisfying to measure according to the IEC-64100-11 standard since microphones should be located directly downstream of the turbine, where the maximum noise levels are expected. In this sense, the IEC standard is a worst case situation. Yet, the noise generation mechanisms (e.g. trailing edge noise considered as one of the most potent source of noise in the audible range) present strong directivity features [1, 3]. These effects are not accounted for in the measurements according to the above standard.

Another aspect of wind turbine noise is the fact that multiple noise generation mechanisms are simultaneously at play. These can be segregated in two main categories: mechanical and aerodynamic noise. Mechanical noise results from structural vibrations of the turbine components (tower, nacelle and blades) as well as gear noise. Usually, it is identified as tonal noise with frequencies associated to the eigenfrequencies of these components or to the rotational speed of the shaft or the gear components. Although potentially annoying and subject to regulations related to tonal noise, mechanical noise is not considered herein. The present study concentrates on aerodynamic noise, i.e. noise generated by the interaction of turbulent vortices with the blade surfaces. These turbulent features can be self-generated, as it is the case for the turbulent boundary layer flow developing along the blade airfoil sections producing noise when passing by the trailing edge. Alternatively, they can originate from the turbulent atmospheric flow impacting the blades or some other external source of turbulence (e.g. wake from an upstream turbine).

Aerodynamic noise generation involves complex phenomena and their mutual interactions. Firstly, fluid flow turbulence is a difficult topic with highly non-linear processes which are not trivial to predict. Most of the theory of turbulence is based on statistical averaging which somehow facilitates some aspects of flow prediction in contrast to the deterministic prediction of the chaotic behavior of the turbulent structures. This is quite relevant for wind turbine noise generation since the time-scales of the turbulent motions generating noise are quite small compared to the time-scales of the parameters influencing the wind turbine operation (e.g. changing mean wind speed over the rotor disk or rotational speed). Secondly, turbulence interaction with the hard surfaces generating noise are also rather complicated phenomena, e.g. noise scattering at the trailing edge. As a consequence, accurately predicting noise from wind turbines can be challenging.

Wind turbine manufacturers have a long practical experience of noise emissions from their wind turbines and have access to a lot of noise measurement data. To predict the noise emission from a turbine, in many cases they rely on semi-empirical models which can be accurately tuned thanks to the above practical experience and know-how. The next step in developing modeling tools capable of predicting wind turbine noise is to introduce more physics in the models and try to describe more faithfully the actual processes involved. This may become a critical asset as wind turbine technology develops with the use of advanced aerodynamic features such as flaps, morphing blades, winglets, etc.

To the best authors' knowledge, there does not exist a commercial simulation tool that is dedicated to the prediction of wind turbine noise as a source, although several of these codes can be used in this context []. As a result, wind turbine manufacturers and research institutions alike separately are developing their own prediction tools. When wind turbine manufacturers can rely on their expertise and historical data, it is sometimes difficult for the researchers to find reliable data to validate their models. Contrastingly, the manufacturers do sometimes have limited resources to develop more advanced simulation tools and usually rely on their existing more empirical tools. In both cases, exchanging experience and comparing results may benefit the two communities.

The aim of the present study is to define a comparison benchmark for wind turbine noise simulation codes. This initiative was taken as part of IEA Wind TCP Task 39 (Quiet Wind Turbine Technology) in collaboration with IEA Wind TCP Task 29 (Analysis of Aerodynamic Measurements). The comparisons are based on an existing wind turbine which was extensively measured during the DANAERO project [5, 6]. These measurements were conducted on is a 2.3 MW NM80 wind turbine located in Tjæreborg, Denmark. One of the blades was specifically manufactured for this project and extensively equipped with aerodynamic sensors, as well as surface pressure high-frequency microphones flush-mounted in the outer part of the blade which are relevant for studying aeroacoustic emissions. Some noise measurements according to the IEC-64100-11 standard also exists and may become part of the present benchmark once this has been negotiated and agreed with the current owner of these data.

The first objective of this comparison benchmark is to make sure that the noise predictions from the different codes are based on (nearly) identical aerodynamic data. Indeed, aerodynamic noise is by essence driven by aerodynamic quantities. In this respect, this benchmark is actively connected to the IEA Wind TCP Task 29 Phase IV which currently focuses on using the DANAERO database to validate aeroelastic codes for wind turbines. Therefore, the present study also includes the validation of a restricted set of aerodynamic data considered as crucial for accurately evaluating the noise emissions. The validation of the aerodynamic noise predictions is the core objective of the present benchmark. This is dealt with in two steps. Firstly, the surface pressure fluctuations measured with high-frequency microphones on the blades can be used to partly validate noise prediction codes, particularly for trailing edge noise but possibly turbulent inflow noise as well. Secondly, the noise emissions of the whole turbine in different configurations are investigated.

## 2. General description of the benchmark

### 2.1. Generalities

The present benchmark is a combination of a series of code validation through simplified test cases and actual measurement data. In the simplified cases, the analysis of the results should reveal some shortcomings of the actual numerical models and their implementation. In particular, some of these test cases will assume axial symmetry of the flow around the rotor axis and this symmetry should be reflected in the computed results, both aerodynamic and acoustic ones. Furthermore, comparisons between results from the various codes should bring some light on the various methods, assuming that high-fidelity models such as CFD can be taken as reference. Concerning the use of actual measurement data, those collected during the DANAERO experiment will be considered.

Briefly, the DANAERO experiment is a series of measurement campaigns conducted in year 2009

**Fig. 1 The NM80 wind turbine in Tjæreborg**

on a 2.3MW NM80 wind turbine with a hub height of 60 m [5] (see Fig. 1). One of the three blades of the turbine was specifically manufactured for this experiment and equipped with multiple sensors. Aerodynamic sensors (pressure taps, Pitot tubes, microphones) are distributed along the blade span at several given radii (see Fig. 2). The blade is a LM 38.8 m attached to the hub at a radius of 1.24 m from the rotor centre. Therefore, the rotor radius at the blade tip is 40.04 m. A met mast located near the turbine was used to monitor atmospheric conditions. The project also included a series of wind tunnel experiments for which 2D reproductions of given blade airfoil sections were measured. These are not considered as part of the present benchmark so far. Note that surface pressure microphones were flush-mounted on the blade near the outer most instrumented radial section. These measurements are quite relevant for the validation of noise emission models (i.e. trailing edge noise, and possibly turbulent inflow noise).

In the present benchmark, we are interested in validating:

- The aerodynamic part for the wind turbine noise codes using pressure tap sensors and Pitot tubes. These validations are a subset of those conducted as part of Task 29 Phase IV Case IV.1 and therefore mainly orientated toward participants to the present benchmark who do not participate to Task 29.

- The estimation of turbulent boundary layer quantities near the trailing edge relevant for trailing edge noise modeling. These quantities were not measured during the measurement campaigns, but validation will be based on cross- checking the results obtained by the various participants (and existing experience on this type of data, e.g. BANC benchmark [2]).

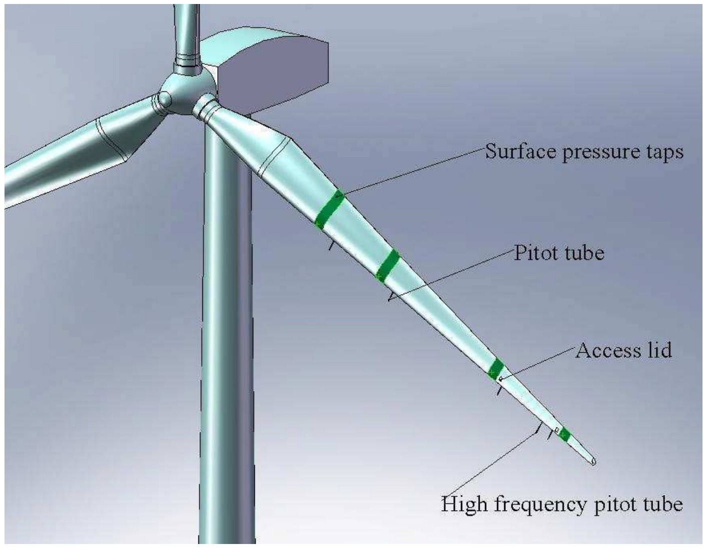


**Fig. 2 Equipment on the LM 38.8 m blade**

- The estimation of the surface pressure fluctuations (more specifically their spectra) for simulation codes using an approach that do provide such quantity. This validation is mainly relevant for turbulent inflow and trailing edge noise prediction models. The validation can be performed using measurement data from surface pressure microphones on the test blade.

- The prediction of the acoustic noise immission in the far-field (in fact at the distance recommended by the IEC 61400-11 standard). The participants are expected to provide their turbulent inflow and trailing edge noise predictions, but may also include other noise sources (e.g. separation noise if separation is detected, tip noise) if they wish so.

Furthermore, according to the previous description of the benchmark, the benchmark is divided into 3 rounds:

- Round #1 is concerned with the validation of the codes for four idealized cases including symmetrical cases, as well as rigid and flexible rotors. Two parameters are varied in order to quantify their influence on the acoustic results: the rotor rotational speed and wind shear.

- Round #2 is concerned with actual cases from the DANAERO experiment. The specific aim of this round is to compare numerical results with existing measurement data.

- Round #3 is concerned with comparisons of the wind turbine noise codes by calculating noise characteristics as a function of wind speed. Noise was not measured as part of the DANAERO experiment, but noise measurements were conducted as part of the certification procedure for this turbine and may possibly be used in this round for validation. For the time-being, the description of Round #3 is tentative and will be refined at a later stage.

Note that the two first rounds are integrated parts of IEA Wind TCP Tasks 29 & 39, while the third round is more orientated toward participants of Task 39. In this paper, we are only interested in the first round of this benchmark.

## 2.2. Test cases

As mentioned above, the benchmark is divided into 3 rounds. Each round contains a number of test cases to be simulated. The specific geometrical and aerodynamic inputs for each test case are shortly described in this section for Round #1. The results to be provided are specified in the following section.

For the **Round #1**, there are 4 test cases defined as follows:

**Case 1.1**
Same as Task 29 Case IV.1.1 and provide comparison results (i.e. aerodynamic and boundary layer quantities, surface pressure near leading and trailing edge, and immission noise) as specified in Section 3 below. The specifications of Case IV.1.1 amounts to an axi-symmetric configuration (no-rotor tilt or yaw, no tower shadow, no wind shear, no inflow turbulence, but the pre-bend is included) and a rigid rotor (i.e. no aeroelastic deformation of the blades).

**Case 1.2**
Same as Task 29 Case IV.1.2 and provide comparison results as specified in Section 3 below. The specifications of Case IV.1.2 are identical to Case IV.1.1, but for flexible blades. However, if the participant's wind turbine noise code cannot handle flexible blades, this case should be ignored and the participant should carry on with the following cases, assuming a rigid structure in Round #2 (see below).

**Case 1.3**
Same as Case 1.1, but with a different rotor speed.

**Case 1.4**
Same as Case 1.1, but with wind shear.

The main other parameters common to all calculations of Round #1 are reported in Table1. Note that the turbulence intensity and length scalse specified herein are only meant for the turbulent inflow noise modeling, not the atmospheric wind speed impacting the turbine for the aero-elastic calculations.

## 2.3. Results to deliver

The results that participants to the benchmark should deliver can be divided into 4 sets.

The first set is concerned with aerodynamic data at the 3 radius locations along the blades. The quantities of interest are mainly relative velocity (with and without induction), angle of attack, aerodynamic forces (incl. lift and drag) and coefficients ($C_L$ and $C_D$, respectively), as a function of time and/or blade azimuth angle. In addition, pressure coefficients around the blade are investigated.

The second set of data is related to trailing edge noise modeling. The results to deliver are quantities across the boundary layer near the trailing edge, both on pressure and suction sides, such as velocity profiles, turbulent kinetic energy, turbulent length scales, and integral quantities such as boundary layer thickness or displacement thickness.

The third set is concerned with surface pressure spectra near the trailing edge and the leading edge, which are of potential interest for trailing edge and leading edge noise, respectively.

The fourth and last set are the noise immission levels at pre-defined observer locations around the turbine on the ground, as well as one location at hub height directly downwind of the turbine. This

**Table 1 Main computational input parameters for Round #1.**

| Quantity | Value |
|---|---|
| Tilt | $0^o$ |
| Coning | $0^o$ |
| Tower shadow | None |
| Air density | 1.231 kg/m$^3$ |
| Temperature | 19$^o$C |
| Wind speed | $V_H = 6.1$ m/s |
| Wind shear | None |
| Turbulence intensity | 8.96% |
| Turbulence length scale | 39 m |
| Rotor speed | 12.3 rpm |
| Blade pitch angle | $1.5^o$ ($>0$ nose down) |
| Yaw error angle | $0^o$ |
| Transition location | $x/C = 0.065$ (Suction side) |
| Transition location | $x/C = 0.20$ (Pressure side) |

last noise immission location is dedicated to check the sanity of the numerical models with respect to the axial symmetry defined in Round #1 (see above).

## 3. Preliminary results and comparison examples

As none of the participants have sent their results at the time of writing, some of the expected results are shown in this section in order to illustrate the specificities of the different test cases.

### 3.1. Aerodynamic results

In figure 3, some aerodynamic data on a given blade at the outer most radial position $r = 37$ m are plotted as a function of its azimuth angular position $\psi$ for the 4 considered test cases. The quantities are the effective velocity, the angle of attack, the lift and drag coefficients. As expected, for test cases 1.1, 1.2 and 1.3 (i.e. without shear), the aerodynamic quantities do not vary with the azimuth position. Contrastingly, these quantities are a function of the azimuth for test case 1.4, which includes a wind shear, thereby breaking the symmetry with respect of the rotor axis as discussed earlier. Note that the angle of attack, as well as lift and drag, are highest when the blade points upwards (i.e. for $\psi = 0^o$). Test case 1.3 exhibits a higher effective velocity because of the higher rotational speed. Furthermore, it can be noticed that the blade flexibility for test case 1.2 also modifies the aerodynamic properties with a higher angle of attack, at least at the considered radius.

### 3.2. Noise immission results

As the main goal of this benchmark is to validate wind turbine noise simulation code, a few examples of noise immission results in the vicinity of the turbine are shown here.

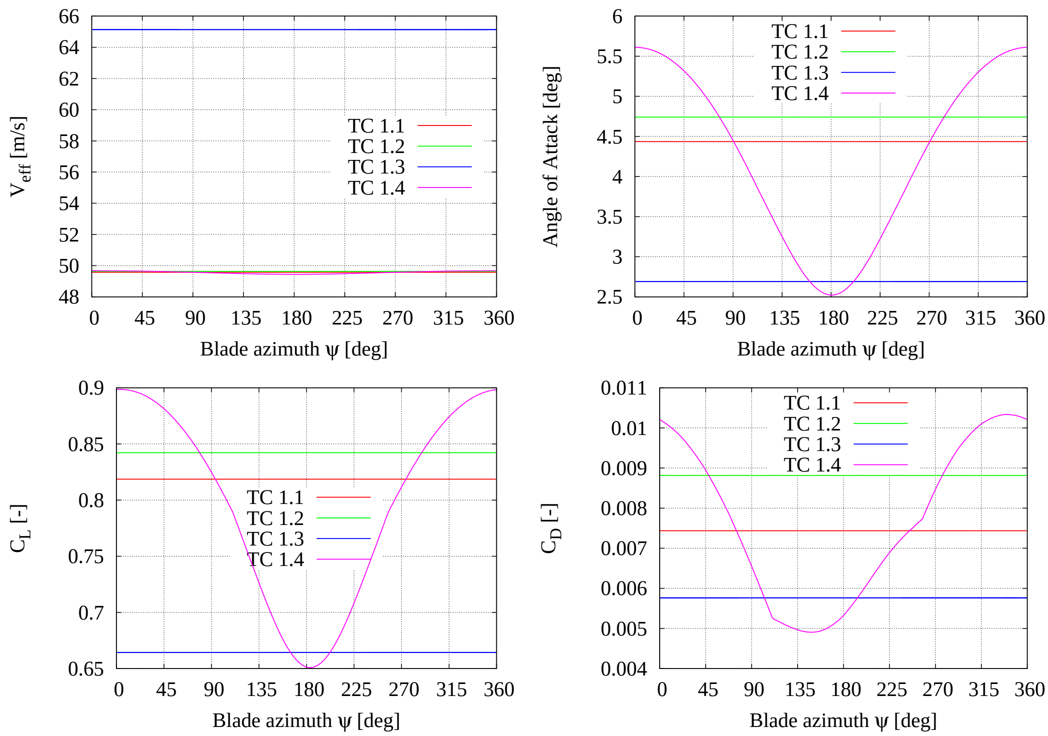


**Fig. 3 Aerodynamic quantities as a function of blade azimuth location ($\psi = 0^\circ$ when the blade points up)**

The whole turbine noise immissions (i.e. the contributions of the noise emissions are integrated over the whole span of the 3 blades and over the whole frequency range) for the 4 test cases are plotted as a function of the azimuth of blade #1 during one of its revolution in Figs. 4, 5 and 6. In the first two figures, the immission location (denoted as P13) is directly downwind of the rotor at hub height. Therefore, this latter point is located on the rotor axis since the rotor is not tilted. In the third figure, the immission point (denoted as P7) is at the IEC standard position, directly downwind of the turbine on the ground. Furthermore, in these figures the noise levels are displayed by adding up all considered noise sources, i.e. here turbulent inflow noise, trailing edge noise and stall noise, as well as individually in the separate sub-figures.

As expected for the results at P13 in Fig. 4, the symmetry of the flow for test cases 1.1, 1.2 and 1.3 results in constant noise levels. However, for an asymmetrical flow field (i.e with wind shear for test case 1.4), the noise levels exhibit temporal variations, in particular for the trailing edge and stall noise, whereas the turbulent inflow noise appears insensitive to the wind shear. The overall noise is slightly influenced by the shear. In the case of A-weighted noise as displayed in Fig. 5, the stall noise becomes dominant and the temporal variation of noise levels become apparent for the overall noise. It may be surprizing that stall noise is dominant in the present configuration. This is investigated below. Before that, it should be noted that the noise immissions at P7 in Fig. 6 illustrate the fact that this position breaks the symmetry of the noise emission as a result of the noise sources directivity.

In order to study the noise emissions in more details, map of the noise sources across the rotor disk are plotted, once again both for all added-up noise sources and individually. These maps represent the elementary contribution to the noise immission levels at given observer locations (i.e.

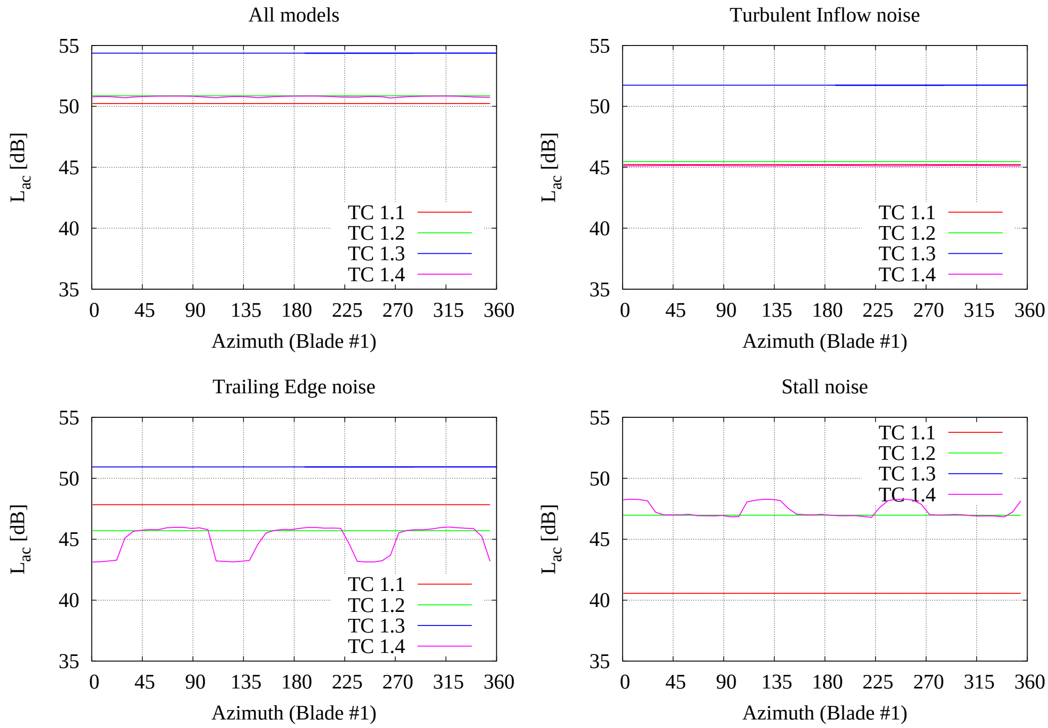


**Fig. 4 Noise immission at P13 (downwind of rotor at hub height) as a function of blade #1 azimuth location**

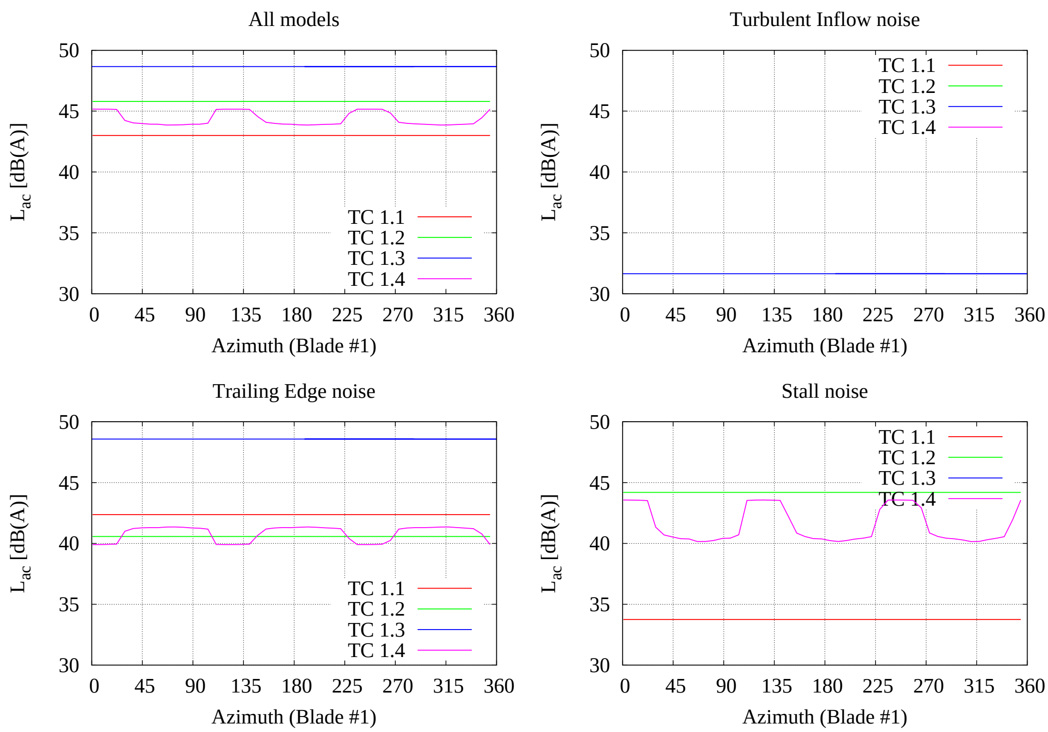


**Fig. 5 A-weighted noise immission at P13 (downwind of rotor at hub height) as a function of blade #1 azimuth location**

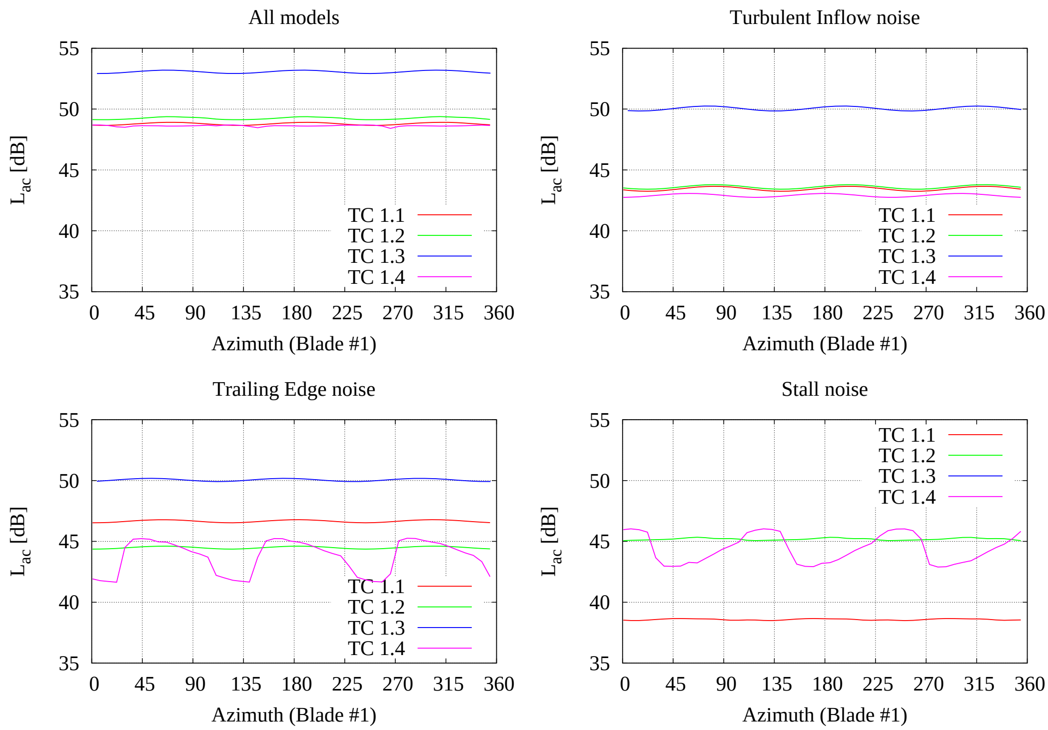


**Fig. 6 Noise immission at P7 (downwind of rotor on the ground) as a function of blade #1 azimuth location**

P7 or P13 here) from the local noise emissions across the rotor disk. Let us first consider test case 1.1. The map for position P13 is displayed in Fig. 7. The symmetry of the noise emissions is clear. Furthermore, it can be seen that stall noise is concentrated in the inner region of the rotor disk/blade where thick airfoil sections can be found, more easily triggering the occurrence of stall. The same map but for position P7 is displayed in Fig. 8. Once again, the asymmetry from the noise directivity patterns becomes apparent and it can be seen that higher noise levels are observed on the lower right part of the rotor disk, both for turbulent inflow and trailing edge noise. This effect is possibly a combination of directivity and the fact that the lower part of the rotor disk is closer to the observer at P7.

Finally, the noise map for test case 1.4 (with wind shear) for an oberver at position P13 is displayed in Fig. 9. It can be seen that stall noise is produced on a large upper part of the rotor disk. Indeed, it is where the wind speed is higher due to the wind shear and angles of attack are also larger (see Section 3.1). However, it was observed in the previous section the angles of attack remain relatively low and it is quite surprizing that stall is so widely spread. This indicates a potential problem in the simulation code which has to be investigated (or alternatively a misinterpretation of the results). As a matter of fact, one of the primary goal of the present benchmark is to detect such inconsistencies in the results and try to improve the prediction tools accordingly.

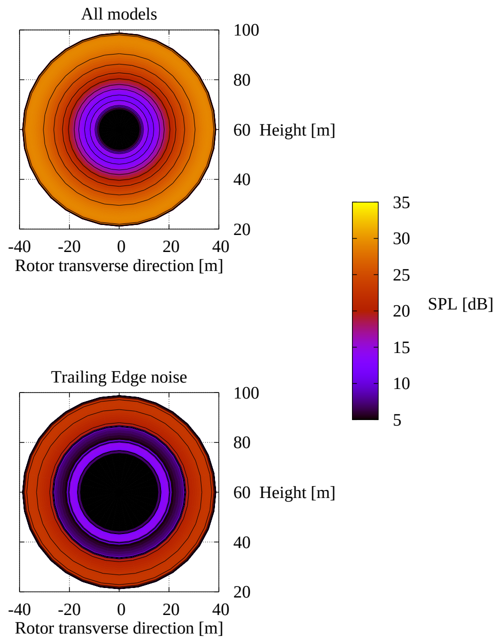


**Fig. 7 Noise immission map at P13 (downwind of rotor at hub height) as seen from upwind the turbine - Test case 1.1.**

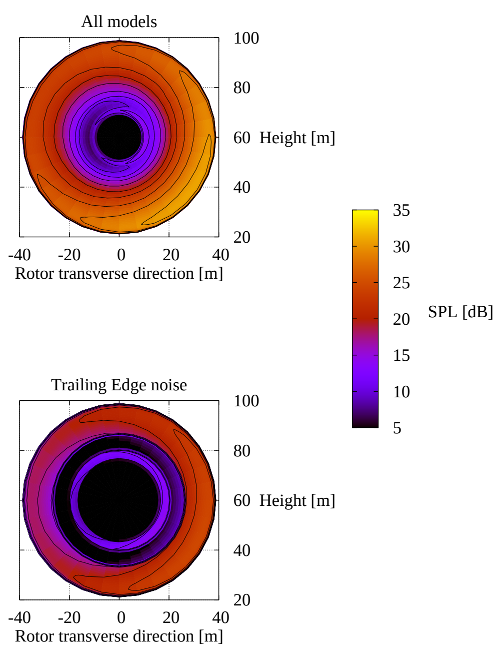


**Fig. 8 Noise immission map at P7 (downwind of rotor on the ground) as seen from upwind the turbine - Test case 1.1.**

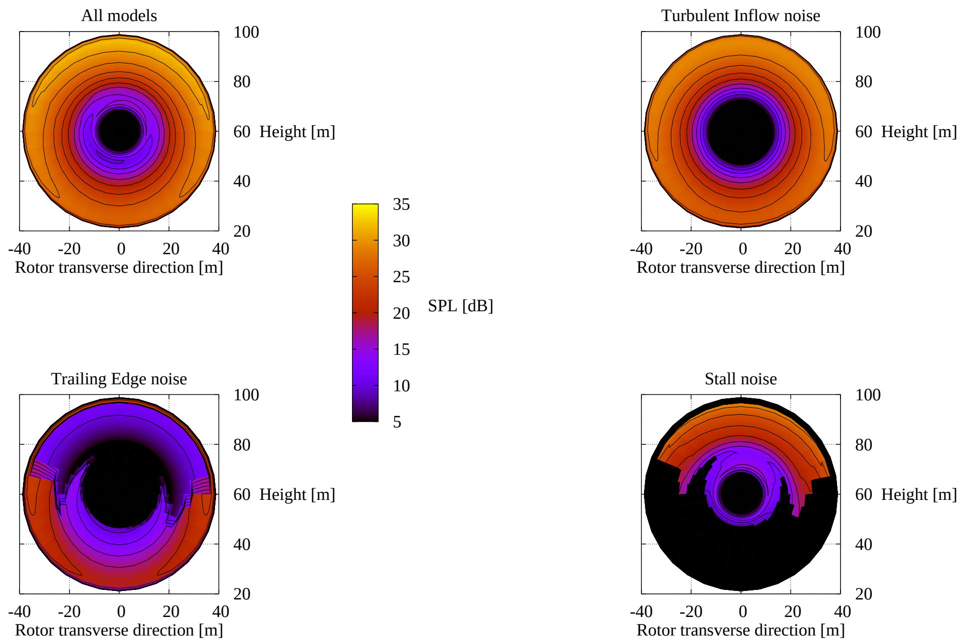


**Fig. 9 Noise immission map at P13 (downwind of rotor on the ground) as seen from upwind the turbine - Test case 1.4.**

## 4. Conclusion

A benchmark for wind turbine noise simulation codes comparison and validation is proposed. The main details of the numerical inputs to the various test cases have been presented (at least for the first round of this benchmark).

At the time of writing, none of the participants have had time to perform the required computations and send their results. However, it is expected that a number of participants will have conducted these before the start of the conference, and that comparisons and analysis of the results can be presented then.

A tentative timeline for the continuation of this benchmark follows. As mentioned above, it is expected that the results of the first round can be analyzed at the WTN 2019 conference, as well as during the next IEA Wind TCP Task 39 meeting which is planned as a side-event to the conference. Round #2 should be conducted during the second semester of year 2019, and Round #3 probably during the first semester of year 2020. However, conclusions from the initial analyses may alter this timeline. In particular, it may be necessary to come back on specific issues of the test cases if difficulties in understanding the results and their comparisons do arise.

## Acknowledgments

This work was partly supported by the EUDP-2016 project Jr.nr. 64016-0056 funded by the Danish Energy Agency (Energistyrelsen). In addition, the present benchmark is conducted as a sub-task of the IEA Wind TCP research Task 39 (Quiet Wind Turbine Technology), as well as a part of IEA Wind

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# ANNEX 6

## IEA Wind Task 39 – Quiet Wind Turbine Technology

## WIND TURBINE NOISE CODE BENCHMARK (Phase I)

***In coordination with:***

## IEA Wind Task 29 (Phase IV) – Wind Turbine Aerodynamics

## TASK IV.3.7: ACOUSTICS

# Definition of three rounds of calculations on DANAERO experiment – Aerodynamics & acoustics comparisons

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### *Introduction*

The aim of this benchmark is to compare and validate wind turbine rotor noise codes that are developed by the participants of IEA Wind Task 29 & Task 39. Task 39 aims at coordinating activities related to wind turbine acoustics across countries, while Task 29 is mainly concerned with aerodynamic and aeroelastic features but it also has a task (officially denoted as Task IV.3.7) dedicated to acoustics. Here, the focus is on aerodynamic noise generation, hence mechanical noise as well as long range propagation effects are not considered, at least in the first phase of this benchmark. So far, the benchmark is divided into 3 rounds which will be dealt with incrementally in time. The 2 first rounds are shared activities between Tasks 29 & 39, while the third round is more specific to Task 39. Further rounds may be defined by the participants in the future according to the conclusions of this first phase, possibly identifying certain aspects that have to be clarified, and/or for broadening the scope.

This document introduces shortly the technical details of the wind turbine and the experimental conditions that are considered for the present benchmark. More details about the required computational set-up for the simulations can be found in the definition of the IEA Wind Task 29 aeroelastic validation cases that are linked to the present benchmark (see below and Annex). The test cases defining the present benchmark and their specific operational conditions, as well as results to provide for the comparisons, are described in the following sections. A timeline for the benchmark is also proposed.

### *1. General description of the benchmark*

The first round of the present benchmark is strongly connected with the first round of calculations for aeroelastic codes as part of IEA Wind Task 29, Phase IV – Case IV.1. The latter is based on measurement data from experiments on the NM80 wind turbine which were

conducted as part of the DANAERO project. The details of the DANAERO experiments and all technical data relevant for this case can be found on the share website:
https://share.dtu.dk/sites/IEA-Task-29_293350
Note that access to this website is granted individually and that access is restricted to participants who are active members of Task 29. Contact Helge Aa. Madsen (email: hama@dtu.dk) or Gerard Schepers (email: gerard.schepers@tno.nl) for more information.

Briefly, the DANAERO experiment is a series of measurement campaigns conducted on a 2.3MW NM80 wind turbine in year 2009. One of the three blades of the turbine was specifically manufactured for this experiment and equipped with multiple sensors. Aerodynamic sensors (pressure taps, Pitot tubes, microphones) are distributed along the blade span at several given radii. The blade is a LM 38.8m attached to the hub at a radius of 1.24m from the rotor centre. Therefore, the rotor radius at the blade tip is 40.04m, which includes the pre-bend of the blades. A met mast located near the turbine was used to monitor atmospheric conditions. Note that the project included a series of wind tunnel experiments for which 2D reproductions of given blade airfoil sections were measured. These are not considered as part of the present benchmark so far.

The reason for the link between Tasks 29 and 39 is that wind turbine aerodynamic noise is mainly driven by the flow field around the turbine. Aerodynamic data are typically used as inputs of the noise calculation methods. Therefore, for validating and benchmarking the participants' wind turbine noise codes, it is necessary to ensure that the aerodynamics around the turbine is correctly modelled in the first place. In this context, the participants of Task 39 are encouraged to participate to the Task 29 comparison Case IV.1. This should greatly facilitate their participation to the present benchmark since some identical test cases and similar comparisons, as far as the aerodynamics is concerned, are conducted in the two tasks. Additional test cases in the present benchmark involve variations of some parameters that are considered as sensitive for the noise emissions.

In the present benchmark, we are interested in validating:

1) the aerodynamic part for the wind turbine noise codes using pressure tap sensors and Pitot tubes. These validations are a subset of those conducted as part of Task 29 Phase IV Case IV.1 and therefore mainly orientated toward participants to the present benchmark who do not participate to Task 29.

2) the estimation of turbulent boundary layer quantities near the trailing edge relevant for trailing edge noise modelling. These quantities were not measured during the measurement campaigns, but validation will be based on cross-checking the results obtained by the various participants (and existing experience on this type of data, e.g. BANC benchmark).

3) the estimation of the surface pressure fluctuations (more specifically their spectra) for simulation codes using an approach that do provide such quantity. This validation is mainly relevant for turbulent inflow and trailing edge noise prediction models. The validation can be performed using measurement data from surface pressure microphones on the test blade.

4) the prediction of the acoustic noise immission in the far-field (in fact at the distance recommended by the IEC 61400-11 standard). The participants are expected to provide their turbulent inflow and trailing edge noise predictions,

but may also include other noise sources (e.g. separation noise if separation is detected, tip noise) if they wish so.

The benchmark is divided into 3 rounds, which closely follows the approach in Task 29 (at least for the first round and to some extent for the second):

**Round #1** is concerned with the validation of the codes for four idealized cases. For the first one (Case 1.1), the rotor is rigid and the flow onto the rotor is axi-symmetric (assuming a simplified geometry of the rotor and no shear). The second one (Case 1.2) is identical to the first case, but for a flexible rotor. Two additional cases (Cases 1.3 and 1.4) with different rotor speed and wind shear are also specified. The aim of this first round is to check the sanity of the codes. The quantities to compare consist of some aerodynamic parameters particularly relevant to aeroacoustics (including surface pressure spectra near the trailing edge) and acoustic noise in the far-field.

**Round #2** is concerned with actual cases from the DANAERO experiment. The specific aim of this round is to compare numerical results with existing measurement data.

**Round #3** is concerned with comparisons of the wind turbine noise codes by calculating noise characteristics as a function of wind speed. Noise was not measured as part of the DANAERO experiment, but noise measurements were conducted as part of the certification procedure for this turbine and may possibly be used in this round for validation. For the time-being, the description of Round #3 is tentative and will be refined at a later stage.

Note that the two first rounds are integrated parts of Tasks 29 & 39, while the third round is more orientated toward participants of Task 39.

## *2. Test cases to be considered*

As mentioned above, the benchmark is divided into 3 rounds. Each round contains a number of test cases to be simulated. The specific geometrical and aerodynamic inputs for each test case are described in this section. The results to be provided are specified in the following section.

Note that in each round, the participants are invited to consider all test cases. However, <u>if a participant is facing a lack of time and/or computational resources, it is still possible to consider only a restricted number of test cases</u>. The test cases are numbered in decreasing order of importance in each round, i.e. the participants are at least expected to consider Case 1.1 in Round #1, and Case 2.1 in Round #2. However, *Case 1.2 is an exception* and it can be considered as less relevant than Case 1.3 and Case 1.4. Thus, these two latter cases (one or the other, or both) should be considered before conducting Case 1.2 in Round #1.

In this section, the mean wind shear is defined by a power law for which the wind speed at height $h$ is defined as $V(h)=V_H\times(h/H)^\beta$ where $H$ is the hub height ($H$=60m), $V_H$ is the mean wind speed at hub height, and $\beta$ the power coefficient.

The atmospheric turbulence intensity *TI* is defined using the variance of the wind speed at hub height divided by the mean wind speed at hub height. These quantities are measured using a sonic anemometer located on the nearby met mast. The sampling rate is 35 Hz and *TI* is computed based on 10 mins recorded time-series. The turbulence integral length scale $L_{int}$ is deduced by fitting the spectra of the 3 velocity components measured by this anemometer to the Mann model which is a dedicated model for atmospheric turbulence.

The yaw error angle $\theta$ is defined as positive (HAWC2-convention) when the wind comes from the right, seen from the turbine looking upstream of the rotor (see Figure 1). In other words:

$$\theta = \text{Wind direction angle} - \text{Turbine yaw angle}$$

where the wind direction and turbine yaw angles are positive clockwise when looking from above the turbine. The reference angle is set to the North direction, i.e. wind direction and turbine yaw angles are 0 when the wind is coming from the North and when the rotor upstream direction is pointing North, respectively.

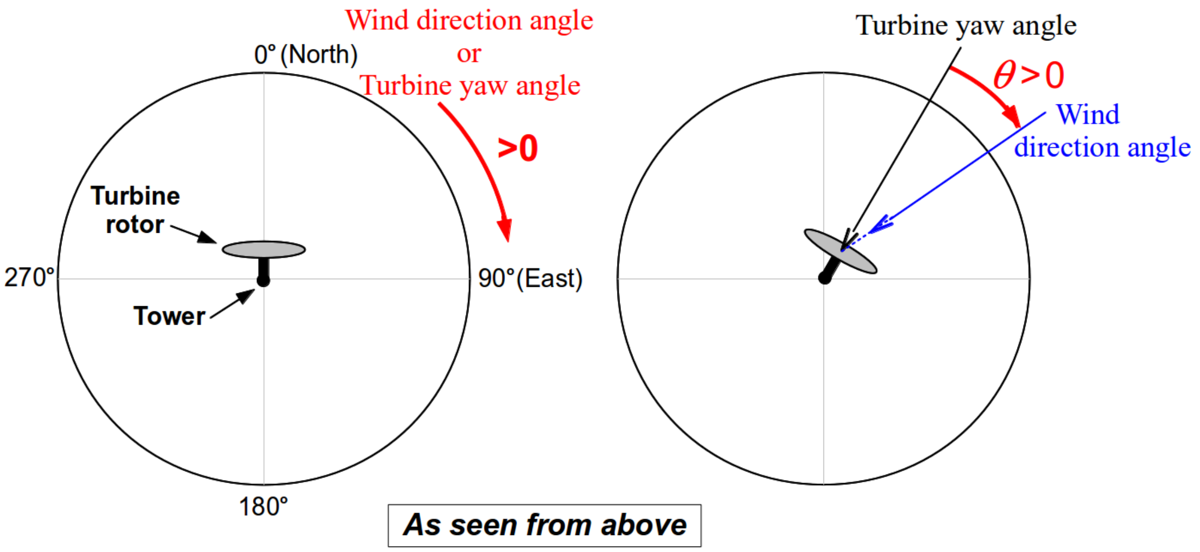


**Figure 1 – Orientation for the wind direction, turbine yaw, and yaw error angles**

Boundary layer transition locations $x_{tr,s}/C$ and $x_{tr,p}/C$ ($C$ being the chord) on the suction and pressure sides, respectively, of the test blade could be derived from the surface pressure microphone measurements during the DANAERO experiment. The microphones were installed at a single radial position along the blade ($r$ = 37.04m, $r/R_{tip}$ = 92.5% , see more details below in Section 3) and therefore, transition location is only available at this position. These locations are therefore specified for each test case below as approximations. Indeed, transition location may be slightly varying as the blade rotates (and obviously it may vary significantly along the blade span). It is left to the participants to enforce these specified transition locations or to use a transition model of their choice. This is particularly relevant for surface pressure spectra and trailing edge noise modeling (see Section 3). Note that the blade surfaces were not tripped.

The 3 rounds are detailed below:

**Round #1: Simplified conditions**
Case 1.1: Same as Task 29 Case IV.1.1 and provide comparison results (i.e. aerodynamic and boundary layer quantities, surface pressure near leading and trailing edge, and immission noise) as specified in Section 3 below. The specifications of Case IV.1.1 amounts to an axi-

symmetric configuration (no-rotor tilt or yaw, no tower shadow, no wind shear, no inflow turbulence, but the pre-bend is included) and a rigid rotor (i.e. no aeroelastic deformation of the blades).

Case 1.2: Same as Task 29 Case IV.1.2 and provide comparison results as specified in Section 3 below. The specifications of Case IV.1.2 are identical to Case IV.1.1, but for flexible blades. However, if the participant's wind turbine noise code cannot handle flexible blades, this case should be ignored and the participant should carry on with the following cases, assuming a rigid structure in Round #2 (see below).

Case 1.3: Same as Case 1.1, but with a different rotor speed.

Case 1.4: Same as Case 1.1, but with wind shear.

The computational details for Cases 1.1-1.4 are reported below:

- Case 1.1 (Identical to Task 29: Case IV.1.1) - Axi-symmetric
    - Rigid construction
    - No tilt, no tower shadow
    - Pre-bend is included
    - Air density $\rho$ = 1.231 kg/m$^3$ – Temperature $T$ = 19$^o$C
    - Wind speed: $V_H$ = 6.1 m/s
    - No wind shear
    - Atmospheric turbulence parameters: $TI$ = 8.96% – $L_{\text{int}}$ = 39m
      *Only to be used for the turbulent inflow noise prediction, not for computing the aerodynamic quantities – If the code cannot dissociate these 2 aspects, it is recommended to conduct the two configurations (i.e. with and without atmospheric inflow turbulence)*
    - Rotor speed: 12.3 rpm (constant)
    - Pitch angle: +0.15 degs. to feather (constant, positive nose down)
    - Yaw error angle: $\theta$=0 degs
    - Transition: $x_{tr,s}/C$=0.065 (suction side) - $x_{tr,p}/C$=0.20 (pressure side)

- Case 1.2 (Identical to Task 29: Case IV.1.2) - Axi-symmetric with flexibilities
    - As Case 1.1, but including flexibilities

- Case 1.3 - Axi-symmetric (rigid construction) with higher rpm
    - As Case 1.1, but with different rpm
    - Wind speed: $V_H$ = 6.1 m/s
    - No wind shear
    - Rotor speed: 16.2 rpm (constant)

- Case 1.4 - Axi-symmetric (rigid construction) with wind shear
    - As Case 1.1, but with specified wind shear
    - Wind speed: $V_H$ = 6.1 m/s
    - Wind shear: $\beta$ = 0.3
    - Rotor speed :12.3 rpm (constant)

**Round #2: Real conditions**

Case 2.1 (low wind shear): Similar to Case 1.2 but for real conditions, i.e. including tower shadow, rotor tilt and yaw error, wind shear, inflow turbulence as specified in more details below. Here and in the following Cases 2.2 to 2.5, the atmospheric turbulence should be used both for the aerodynamic and the turbulent inflow noise calculations. Furthermore, the blades and tower should be flexible, but these can be kept as rigid if the simulation code cannot handle this option – Additional note: Wind speed $V_H$ = 6.39 instead of 6.1 m/s, and also a slightly different air density (corresponding to measurements conducted on 16/07/2009 – 12:54).

Case 2.2 (higher rpm – low wind shear): Similar to Case 1.3 but for real conditions as Case 2.1 and specific operational conditions as described in more detail below (16/07/2009 – 14:09).

Case 2.3 (higher wind shear – below rated power): Similar to Case 2.2 but higher wind speed and higher wind shear (01/09/2009 – 10:10).

Case 2.4 (higher wind shear – above rated power): Similar to Case 2.3 but for even higher wind speed (01/09/2009 – 15:14)

Case 2.5 (higher wind shear – above rated power): Similar to Case 2.4 but with a large wind turbine rotor yaw error relative to the inflow (01/09/2009 – 12:12)

The computational details for Cases 2.1-2.5 are reported below:

- Case 2.1 – 16/07/2009 - 12:54-12:55
  - As Case 1.2 (i.e. including flexibilities, if possible), but with real geometry and actual operating conditions
  - Air density $\rho$ = 1.225 kg/m$^3$ – Temperature $T$ = 19$^o$C
  - Wind speed: $V_H$ = 6.39 m/s – Wind shear: $\beta$ = 0.03
  - Atmospheric turbulence parameters: $TI$ = 8.96% – $L_{\text{int}}$ = 39m
  - Rotor speed: 12.26 rpm (constant)
  - Pitch angle: +0.15 degs. (constant, positive nose down)
  - Yaw error angle: $\theta$=+1.4 degs. (Turbine yaw/Wind dir. = 229.0/230.4 degs.)
  - Transition: $x_{tr,s}/C$=0.065 – $x_{tr,p}/C$=0.20 (12:54)

- Case 2.2 – 16/07/2009 - 14:09-14:10
  - As Case 1.2, but with real geometry and actual operating conditions
  - Air density $\rho$ = 1.233 kg/m$^3$ – Temperature $T$ = 18$^o$C
  - Wind speed: $V_H$ = 6.39 m/s – Wind shear: $\beta$ = 0.05
  - Atmospheric turbulence parameters: $TI$ = 10.16% – $L_{\text{int}}$ = 55m
  - Rotor speed: 16.24 rpm (constant)
  - Pitch angle: -1.25 degs. (constant, positive nose down)
  - Yaw error angle: $\theta$=+7.5 degs. (Turbine yaw/Wind dir. = 238.1/245.6 degs.)
  - Transition: $x_{tr,s}/C$=0.065 – $x_{tr,p}/C$=0.20 (14:09)

- Case 2.3 – 01/09/2009 - 10:10-10:11
  - As Case 1.2, but with real geometry and actual operating conditions
  - Air density $\rho$ = 1.218 kg/m$^3$ – Temperature $T$ = 20$^o$C
  - Wind speed: $V_H$ = 9.82 m/s – Wind shear: $\beta$ = 0.30

- Atmospheric turbulence parameters: $TI$ = 5.47% – $L_{int}$ = 5.0m
- Rotor speed: 16.20 rpm (constant)
- Pitch angle: -4.75 degs. (constant, positive nose down)
- Yaw error angle: $\theta$=+4.4 degs. (Turbine yaw/Wind dir. = 162.7/167.1 degs.)
- Transition: $x_{tr,s}/C$=0.015 – $x_{tr,p}/C$=0.58 (10:10)

- Case 2.4 – 01/09/2009 - 15:14-15:15
  - As Case 1.2, but with real geometry and actual operating conditions
  - Air density $\rho$ = 1.222 kg/m$^3$ – Temperature $T$ = 19$^o$C
  - Wind speed: $V_H$ = 12.48 m/s – Wind shear: $\beta$ = 0.12
  - Atmospheric turbulence parameters: $TI$ = 8.39% – $L_{int}$ = 27m
  - Rotor speed: 16.18 rpm (relatively constant, st.dev. +/-0.11)
  - Pitch angle: +4.50 degs. (st.dev. +/-1.035, positive nose down)
  - Yaw error angle: $\theta$=+8.7 degs. (Turbine yaw/Wind dir. = 209.5/218.2 degs.)
  - Transition: : $x_{tr,s}/C$=0.015 – $x_{tr,p}/C$=0.15 (15:14)

- Case 2.5 – 01/09/2009 - 12:12-12:13
  - As Case 1.2, but with real geometry and actual operating conditions
  - Air density $\rho$ = 1.214 kg/m$^3$ – Temperature $T$ = 21$^o$C
  - Wind speed: $V_H$ = 13.38 m/s – Wind shear: $\beta$ = 0.24
  - Atmospheric turbulence parameters: $TI$ = 6.15% – $L_{int}$ = 5.0m
  - Rotor speed: 16.23 rpm (relatively constant, st.dev. +/-0.09)
  - Pitch angle: +5.935 degs. (st.dev. +/-0.801, positive nose down)
  - Yaw error angle: $\theta$=+17.3 degs. (Turbine yaw/Wind dir. = 165.7/183.0 degs.)
  - Transition: : $x_{tr,s}/C$=0.11 – $x_{tr,p}/C$=0.14 (12:12)

**Round #3: Acoustic power curve *(tentative)***
Test Case 3.1: Similar real conditions as in Round #2, but for wind speeds varying from 6m/s to 24m/s by step of 2m/s, *OR* only 6, 8 and 10m/s if the participant has limited available time/computational resources, with given varying rpm and pitch settings (to be announced later on) and a yaw error angle $\theta$ = 0 degs.

More specific details about the computational cases in this 3rd round will be decided later on in the project and communicated to the participants in due time.

## *3. Results to provide for the benchmarking*

Concerning Round #1 of the present benchmark and as mentioned earlier, the participants are advised to participate to Task 29 Phase IV and validate their aerodynamic/structural results to complement this 1st validation round. As a further step for validating aerodynamic quantities relevant for the acoustic emissions, a restricted (compared to Task 29 – Case IV.1) set of aerodynamic data is required as part of the present benchmark. In addition, some boundary layer data near the trailing edge critical for the evaluation of trailing edge noise are also required. Furthermore, for the acoustic part of the codes which is the primary interest here, the participants should provide the surface pressure spectra near the leading and trailing edges (both suction and pressure sides), if these spectra are, or can be, calculated as part of their simulation code for turbulent inflow and trailing edge noise modeling, respectively. Finally, acoustic noise at given observer/listener locations as specified below should be calculated. Hence, the comparison results to be delivered for Round #1 and #2 consist of 4 data sets as detailed below.

Note that if for some reason a participant cannot deliver some of the required data (e.g. because of lack of resources, or if the simulation code does not give access to these data), it is possible to skip these data either by not delivering the entire result file, or by entering *NaN* values in the result file if some other quantities in the same file can actually be calculated.

**Aerodynamic data:**
The aerodynamic data should be provided at 3 radial positions along the blade span:

- At $r/R_{tip}$ = 47.6% – Position 5A, $R_{tip}$-$r$ = 21.0m, $r$ = 19.04m
- At $r/R_{tip}$ = 75.0% – Position 8A, $R_{tip}$-$r$ = 10.0m, $r$ = 30.04m
- At $r/R_{tip}$ = 92.5% – Position 10E, $R_{tip}$-$r$ = 3.0m, $r$ = 37.04m

where $r$ and $R_{tip}$ are radius positions from the rotor center. Note that the latter radii are in fact positions along the rotor radius axis perpendicular to the drive-train axis (which is tilted for Cases 2.1-2.5). Thus, the rotor radius axis does not follow the blade axis itself since the latter is pre-bent.

The quantities to be provided for each test case (Cases 1.1 to 2.5 as defined in Section 2) and at each radial position are:

- Relative velocity $V_{rel}$ [m/s] (norm of rotational velocity and far-field wind speed projected in the plane of the blade airfoil section at considered radius)
- Effective velocity $V_{eff}$ [m/s] (relative velocity including local rotor induction)
- Normal aerodynamic force $F_N$ [N/m] and normalized airfoil coefficient $C_N$ [-]
- Tangential aerodyn. force $F_T$ [N/m] and normalized airfoil coefficient $C_T$ [-]
- Angle of Attack $\alpha$ [degs.]
- Lift force $F_L$ [N/m] and normalized airfoil coefficient $C_L$ [-]
- Drag force $F_D$ [N/m] and normalized airfoil coefficient $C_D$ [-]
- Surface pressure $p$ [Pa] distribution around the airfoil blade section at the given radii (relative to the ambient pressure $p_\infty$) and pressure coefficient $C_p$ [-] distribution around the airfoil

In the above definitions, the aerodynamic forces are expressed in N/m which refers to Newton per meter of blade span, and a normalized airfoil coefficient $C_X$ is related to the corresponding aerodynamic force $F_X$ as:

$$C_X = F_X\,(\text{x1m}) \,/\, (\,0.5\,\rho\,V_{rel}^2\,C\,) \qquad (X = N, T, L, D)$$

and:

$$C_p = (\,p_\infty - p\,) \,/\, (\,0.5\,\rho\,V_{rel}^2\,)$$

Note here that, e.g. for 3D rotor simulation codes, it may be difficult to extract an angle of attack, and thereby lift and drag. The same may hold for the relative velocity, and thereby airfoil coefficients may not be available. In such cases, the participant may leave out these unavailable values and enter a *NaN* value instead in the result files below.

The participants should deliver ASCII files (2 for each radial position and for each test case as defined in Section 2) with the following formats:

# Time [s], Azimuth [deg], $V_{rel}$ [m/s], $V_{eff}$ [m/s], $F_N$ [N/m], $F_T$ [N/m], $C_N$ [-], $C_T$ [-], $\alpha$ [degs.], $F_L$ [N/m], $F_D$ [N/m], $C_L$ [-], $C_D$ [-]

$t_1$ $\psi_1$ $V_{rel,1}$ $V_{eff,1}$ $F_{N,1}$ $F_{T,1}$ $C_{N,1}$ $C_{T,1}$ $\alpha_{L,1}$ $F_{L,1}$ $F_{D,1}$ $C_{L,1}$ $C_{D,1}$

$t_2$ $\psi_2$ $V_{rel,2}$ $V_{eff,2}$ $F_{N,2}$ $F_{T,2}$ $C_{N,2}$ $C_{T,2}$ $\alpha_{L,2}$ $F_{L,2}$ $F_{D,2}$ $C_{L,2}$ $C_{D,2}$

…

$t_N$ $\psi_N$ $V_{rel,N}$ $V_{eff,N}$ $F_{N,N}$ $F_{T,N}$ $C_{N,N}$ $C_{T,N}$ $\alpha_{L,N}$ $F_{L,N}$ $F_{D,N}$ $C_{L,N}$ $C_{D,N}$

[end of file]

where N is the number of computed time-steps $t_i$ (i=1, N) (at least spanning a third of a rotor revolution, the rotor consisting of 3 blades), and the $\psi_i$'s (i=1,N) denote the azimuth positions of the considered blade at time $t_i$. The azimuth angle is set to 0 degs. when the blade is pointing upward, and positive clockwise when looking at the rotor from upstream which corresponds to the actual rotor direction of rotation. The second file format is:

# Time [s], Azimuth [deg], $x/C$ [-], $y/C$ [-], $p$ [Pa], $C_p$ [-]

$t_1$ $\psi_1$ $x_1/C$ $y_1/C$ $p_{1,1}$ $C_{p1,1}$

$t_1$ $\psi_1$ $x_2/C$ $y_2/C$ $p_{2,1}$ $C_{p2,1}$

…

$t_1$ $\psi_1$ $x_M/C$ $y_M/C$ $p_{M,1}$ $C_{pM,1}$

[empty line]

$t_2$ $\psi_2$ $x_1/C$ $y_1/C$ $p_{1,2}$ $C_{p1,2}$

$t_2$ $\psi_2$ $x_2/C$ $y_2/C$ $p_{2,2}$ $C_{p2,2}$

…

$t_2$ $\psi_2$ $x_M/C$ $y_M/C$ $p_{M,2}$ $C_{pM,2}$

[empty line]

…

…

[empty line]

$t_N$ $\psi_N$ $x_1/C$ $y_1/C$ $p_{1,N}$ $C_{p1,N}$

$t_N$ $\psi_N$ $x_2/C$ $y_2/C$ $p_{2,N}$ $C_{p2,N}$

…

$t_N$ $\psi_N$ $x_M/C$ $y_M/C$ $p_{M,N}$ $C_{pM,N}$

[end of file]

where M is the number of calculation points $x_j$, $y_j$ (j=1, M) defining the airfoil section contour of chord $C$, and where the pressure coefficient distributions are computed. Note that M, and obviously $C$, can vary from one radial position to another.

In order to facilitate the processing of the results, it is suggested to use the following designations for the files containing the results:

aero_sct19m_caseTC_NAME.dat
aero_sct30m_caseTC_NAME.dat
aero_sct37m_caseTC_NAME.dat

cp_sct19m_caseTC_NAME.dat
cp_sct30m_caseTC_NAME.dat
cp_sct37m_caseTC_NAME.dat

where 'TC' should be replaced by the test case number (i.e. 1.1 to 2.5), and 'NAME' by the participant's institution/company name or acronym.

**Boundary layer data:**
As part of trailing edge noise modeling and if these quantities are computed by the participant's simulation code, the following flow quantities across the (turbulent) boundary layer at one position on the suction side and one on the pressure side of the blade should be provided:

- Boundary layer thickness $\delta$ [m]
- Displacement thickness $\delta_1$ [m]
- Momentum thickness $\delta_2$ [m]
- Velocity profile across boundary layer $U(y)$ [m/s]
- Turbulent kinetic energy $k(y)$ [$m^2/s^2$]
- Energy dissipation rate $\varepsilon(y)$ [$m^2/s^3$]
- Turbulence integral length scale $\Lambda(y)$ [m]

where $y$ refers, in the present context, to the distance from the blade surface (preferably perpendicular to it) across the boundary layer. It should be distinguished from the coordinate of the airfoil section contour as introduced above for the pressure distributions in the aerodynamic data.

The boundary layer data should only be provided at the following single radial position (see radius definition above):

- At $r/R_{tip}$ = 92.5% – Position 10E, $R_{tip}$-$r$ = 3m, $r$ = 37.04m

at the 2 following chord positions:

- on suction side at x/C = 93.31% and
- on pressure side at x/C = 90.79%

The participants should deliver ASCII files (2 for each boundary layer location and for each test case as defined in Section 2) with the following formats:

# Time [s], Azimuth [deg], $\delta$ [m] , $\delta_1$ [m] , $\delta_2$ [m]
$t_1$ $\psi_1$ $\delta_1$ $\delta_{1,1}$ $\delta_{2,1}$
$t_2$ $\psi_2$ $\delta_2$ $\delta_{1,2}$ $\delta_{2,2}$
…
$t_N$ $\psi_N$ $\delta_N$ $\delta_{1,N}$ $\delta_{2,N}$
[end of file]

and:

# Time [s], Azimuth [deg], $y$ [m], $U$ [m/s], $k$ [$m^2/s^2$], $\varepsilon$ [$m^2/s^3$], $\Lambda$ [m]
$t_1$ $\psi_1$ $y_1$ $U_{1,1}$ $k_{1,1}$ $\varepsilon_{1,1}$ $\Lambda_{1,1}$
$t_1$ $\psi_1$ $y_2$ $U_{2,1}$ $k_{2,1}$ $\varepsilon_{2,1}$ $\Lambda_{2,1}$
…
$t_1$ $\psi_1$ $y_B$ $U_{B,1}$ $k_{B,1}$ $\varepsilon_{B,1}$ $\Lambda_{B,1}$
[empty line]
$t_2$ $\psi_2$ $y_1$ $U_{1,2}$ $k_{1,2}$ $\varepsilon_{1,2}$ $\Lambda_{1,2}$
$t_2$ $\psi_2$ $y_2$ $U_{2,2}$ $k_{2,2}$ $\varepsilon_{2,2}$ $\Lambda_{2,2}$
…
$t_2$ $\psi_2$ $y_B$ $U_{B,2}$ $k_{B,2}$ $\varepsilon_{B,2}$ $\Lambda_{B,2}$
[empty line]
…
…
[empty line]
$t_N$ $\psi_N$ $y_1$ $U_{1,N}$ $k_{1,N}$ $\varepsilon_{1,N}$ $\Lambda_{1,N}$
$t_N$ $\psi_N$ $y_2$ $U_{2,N}$ $k_{2,N}$ $\varepsilon_{2,N}$ $\Lambda_{2,N}$
…

$t_N$ $\psi_N$ $y_B$ $U_{B,N}$ $k_{B,N}$ $\varepsilon_{B,N}$ $\Lambda_{B,N}$
[end of file]

where B is the number of point across the boundary layer (B may be different for the results provided on the suction and pressure sides, respectively).

It is suggested to use the following designations for the files containing the results:

delta_sct37m_xC93ss_caseTC_NAME.dat
delta_sct37m_xC91ps_caseTC_NAME.dat

blayer_sct37m_xC93ss_caseTC_NAME.dat
blayer_sct37m_xC91ps_caseTC_NAME.dat

**Surface pressure spectra:**
As part of trailing edge noise modeling and if available, the participants should provide the 1-sided surface pressure spectra $S_{pp}$ (Unit: dB re 1μPa in 1/3 octave bands centered around 1kHz) as a function of frequency $f$ and the integrated surface pressure spectrum values $L_p$ (without A-weighting in both cases), both as a function of time and the blade azimuth position. The above integration should be performed from 40Hz to 10kHz. The chord positions of measuring microphones located near the trailing edge are specified below.

As part of turbulent inflow noise modeling and if available, similar data as above (i.e. 1-sided surface pressure spectra and integrated spectra) should be provided, once again if the participant's simulation code can provide such data. Microphones positions near the leading edge are specified below.

The surface pressure spectra should only be provided at the following single radial position (see radius definition above):

- At $r/R_{tip}$ = 92.5% – Position 10E, $R_{tip}$-$r$ = 3m, $r$ = 37.04m

Surface pressure spectra $S_{pp}$ $(f)$ and integrated values $L_p$ should be provided at the following 4 microphone positions:

- on suction side at x/C = 93.31% and
- on pressure side at x/C = 90.79% for trailing edge noise,
- on suction side at x/C = 0.51% and
- on pressure side at x/C = 2.22% for turbulent inflow noise.

The participants should deliver ASCII files (2 for each microphone position and for each test case as defined in Section 2) with the following formats:

# Time [s], Azimuth [deg], $L_p$ [dB]
$t_1$ $\psi_1$ $L_{p,1}$
$t_2$ $\psi_2$ $L_{p,2}$
…
$t_N$ $\psi_N$ $L_{p,N}$
[end of file]

and:

# Time [s], Azimuth [deg], $f$ [Hz], $S_{pp}$ [$dB_{1/3}$]
$t_1$ $\psi_1$ $f_1$ $S_{pp,1,1}$

$t_1$ $\psi_1$ $f_2$ $S_{pp,2,1}$
…
$t_1$ $\psi_1$ $f_Q$ $S_{pp,Q,1}$
[empty line]
$t_2$ $\psi_2$ $f_1$ $S_{pp,1,2}$
$t_2$ $\psi_2$ $f_2$ $S_{pp,2,2}$
…
$t_2$ $\psi_2$ $f_Q$ $S_{pp,Q,2}$
[empty line]
…
…
[empty line]
$t_N$ $\psi_N$ $f_1$ $S_{pp,1,N}$
$t_N$ $\psi_N$ $f_2$ $S_{pp,2,N}$
…
$t_N$ $\psi_N$ $f_Q$ $S_{pp,Q,N}$
[end of file]

where Q is the number of frequencies at which the surface pressure spectra are computed (in 1/3 octave bands, see above).

It is suggested to use the following designations for the files containing the results:

lp_sct37m_xC93ss_caseTC_NAME.dat
lp_sct37m_xC91ps_caseTC_NAME.dat
lp_sct37m_xC0051ss_caseTC_NAME.dat
lp_sct37m_xC0222ps_caseTC_NAME.dat

spp_sct37m_xC93ss_caseTC_NAME.dat
spp_sct37m_xC91ps_caseTC_NAME.dat
spp_sct37m_xC0051ss_caseTC_NAME.dat
spp_sct37m_xC0222ps_caseTC_NAME.dat

**Aerodynamic noise:**
Noise immission should be computed at observers located on the ground, i.e. at tower bottom level, and distributed around the turbine at a distance of 100 m from the tower bottom (corresponding to the IEC 61400-11 measurement distance). The results should be provided for (an) observer(s) at least at 1 location directly downstream of the tower (this location is referred to as $P_{down}$), *OR* at 4 locations downstream/upstream/left/right of the tower, *OR* 12 locations with intervals $\Delta\theta$=30 degs. (including $P_{down}$ as one of these 12 locations). The choice of using 1, 4 or 12 locations is left to the individual participant according to its own time/computational/modeling resources to provide these results. Nevertheless and *IN ADDITION*, the noise results should also be provided at one immission location directly downwind of the turbine hub *at hub height* (mainly for Cases 1.1-1.4 for validating the axi-symmetry). Noise should be calculated both as 1-sided frequency-spectra *SPL(f)* (Unit: dB re 1μPa, in 1/3 oct. bands without A-weighting) as a function of time and *one of* the blades azimuth position, and as integrated spectrum values $L_a$ (Unit: dB, integrated from 40Hz to 10kHz without A-weighting) as a function of time and *one of* the blades azimuth position.

In the result files as described below, the participants are expected to provide the individual aerodynamic noise sources individually (if the rotor noise simulation code has this option available, otherwise do not provide them), as well as the overall noise from all these sources. It is expected that at least turbulent inflow and trailing edge noise can be calculated and these should appear as the two first noise sources after the overall noise. The participants may subsequently compute and add in the files the contributions of separation noise, tip noise, etc, and specify them in the first comment line of the files starting with a #.

The participants should deliver ASCII files (2 for each of the 2, 5 or 13 immission locations and for each test case as defined in Section 2) with the following formats:

# Time [s], Azimuth [deg], $L_a$ [dB], $L_{a,TI}$ [dB], $L_{a,TE}$ [dB], $L_{a,SEP}$ [dB], $L_{a,TIP}$ [dB], ...
$t_1$ $\psi_1$ $L_{a,1}$ $L_{a,TI,1}$ $L_{a,TE,1}$ …
$t_2$ $\psi_2$ $L_{a,2}$ $L_{a,TI,2}$ $L_{a,TE,1}$ …
…
$t_N$ $\psi_N$ $L_{a,N}$ $L_{a,TI,N}$ $L_{a,TE,1}$ …
[end of file]

and:

# Time [s], Azimuth [deg], $f$ [Hz], $SPL$ [$dB_{1/3}$], $SPL_{TI}$ [$dB_{1/3}$] , $SPL_{TE}$ [$dB_{1/3}$], …
$t_1$ $\psi_1$ $f_1$ $SPL_{1,1}$ $SPL_{TI,1,1}$ $SPL_{TE,1,1}$ …
$t_1$ $\psi_1$ $f_2$ $SPL_{2,1}$ $SPL_{TI,2,1}$ $SPL_{TE,2,1}$ …
…
$t_1$ $\psi_1$ $f_Q$ $SPL_{Q,1}$ $SPL_{TI,Q,1}$ $SPL_{TE,Q,1}$ …
[empty line]
$t_2$ $\psi_2$ $f_1$ $SPL_{1,2}$ $SPL_{TI,1,2}$ $SPL_{TE,1,2}$ …
$t_2$ $\psi_2$ $f_2$ $SPL_{2,2}$ $SPL_{TI,2,2}$ $SPL_{TE,2,2}$ …
…
$t_2$ $\psi_2$ $f_Q$ $SPL_{Q,2}$ $SPL_{TI,Q,2}$ $SPL_{TE,Q,2}$ …
[empty line]
…
…
[empty line]
$t_N$ $\psi_N$ $f_1$ $SPL_{1,N}$ $SPL_{TI,1,N}$ $SPL_{TE,1,N}$ …
$t_N$ $\psi_N$ $f_2$ $SPL_{2,N}$ $SPL_{TI,2,N}$ $SPL_{TE,2,N}$ …
…
$t_N$ $\psi_N$ $f_Q$ $SPL_{Q,N}$ $SPL_{TI,Q,N}$ $SPL_{TE,Q,N}$ …
[end of file]

It is suggested to use the following designations for the files containing the results:

lac_Pdown_caseTC_NAME.dat (or alternatively: lac_P7_caseTC_NAME.dat)
lac_P*I*_caseTC_NAME.dat
lac_Pdownhub_caseTC_NAME.dat

spl_Pdown_caseTC_NAME.dat (or alternatively: spl_P7_caseTC_NAME.dat)
spl_P*I*_caseTC_NAME.dat
spl_Pdownhub_caseTC_NAME.dat

where the index $I$ runs from 1 to 12. The index '1' corresponds to the upstream location, '4' to the location left of the rotor (when looking from upstream at the rotor), '7' to the downstream location, '10' to the location right of the rotor (when looking from upstream). In the above files designations, 'Pdownhub' refers to the observer location downstream of the turbine at hub height.

## *4. Timeline*

Before defining a timeline for the different rounds of the benchmark, it should be mentioned that it is intended to publish the results of Round #1 (and possibly #2 if enough results can be gathered at that time, see proposed timeline below) as a presentation at the Wind Turbine Noise 2019 (WTN2019) conference organized by INCE-Europe in Lisbon, June 12-14, 2019. This presentation would give rise to a conference paper in the conference proceedings. Participants to the benchmark will be added to the authors' list unless otherwise stated, i.e. a given participant may decide that its results are only anonymously published in the above-mentioned publication, or that its results are kept for comparison as part of the IEA Tasks 29 & 39 only and not published at all.

Furthermore, it is intended to organize the next IEA Wind Task 39 meeting as a side-event to the WTN2019 conference. The results of the benchmark will then be discussed between persons attending to this meeting (possibly remotely).

The following timeline for the several rounds is proposed:

- Round #1: March 15$^{th}$, 2019 (Friday) - Note that this deadline is quite **strict** as the deadline for submitting the final article for the proceedings of the WTN2019 conference is March 22$^{th}$, 2019. However, the participant may deliver the results for this 1$^{st}$ round at a later date. These can be still be added to the conference presentation and/or task meeting discussion if the deadline for Round #2 can be met.
- Round #2: June 7$^{th}$, 2019 (Friday) so that the results can be presented at the next IEA Wind Task 39 meeting as a side event to the WTN2019 conference. However, note that the participants may prefer to deliver the results of Round #1 and Round #2 simultaneously (on March 15$^{th}$, or June 7$^{th}$ if not possible before). Indeed, both rounds differ essentially only by the input parameters to be used for the different simulation test cases. Therefore, working time may be more efficiently used by conducting the 2 rounds simultaneously.
- Round #3 - Sometime around end of 2019 or start of 2020 (to be defined later).

## *ANNEX 1 - Extract from: IEA Task 29, Phase IV: Definition of first round of calculations on DanAero experiment (Case IV.1)*

Information (or more precisely where to find them) about the NM80 wind turbine technical details are reported below.

The turbine data can be found digitally in an Excel sheet on https://share.dtu.dk/sites/IEA-Task-29_293350/Lists/News/DispForm.aspx?ID=4&Source=https%3A%2F%2Fshare%2Edtu%2Edk%2Fsites%2FIEA-Task-29_293350%2FSitePages%2FHome%2Easpx&ContentTypeId=0x0104004B5A174D68045141B59E64500460A769 but **for the first cases tilt angle, and tower shadow effects are neglected. Pre-Bend is included!**

To make sure that everybody uses the same input, the airfoil coefficient data sets are prescribed in the Excel sheet (also see DANAERO_3DA_pc_hama_38.CL.eps)
For the CFD modellers please use the supplied CAD files from the EPOS site (**expected to be uploaded during first week of October**) which you find on:
https://share.dtu.dk/sites/IEA-Task-29_293350/The%20DanAero%20Data%20Base/Forms/AllItems.aspx?RootFolder=%2Fsites%2FIEA-Task-29_293350%2FThe%20DanAero%20Data%20Base%2FTurbine%20model%2FCFD%20modelling&FolderCTID=0x01200010776225236F1A48B82AE11B7D12512A&View=%7BB05E01CB-C5F6-4D9F-A3AD-9CF0B959D925%7D with:

- Design geometry of the blades as supplied by DTU, Please note that the blade geometry does not yet include the pitch angle.
- Note that tower and nacelle effects are neglected

# References

[1] H.Aa. Madsen, C. Bak, U.S. Paulsen, M. Gaunaa, P. Fuglsang, J. Romblad, N.A. Olesen, P. Enevoldsen, J. Laursen, and L. Jensen. *The DAN-AERO MW Experiments Final report*. Technical Report RISO-R- 1726(EN), Technical University of Denmark, 2010.
[2] C. Bak, H.Aa. Madsen, P. Hansen, M. Rasmussen, P. Fuglsang, J. Romblad, N.A. Olesen, *Danaero MW Measurement campaigns on the NM80 2.3 MW Wind Turbine at Tjaereborg 2009* Technical Report RISO-I- 3046(EN), Technical University of Denmark, 2010.
[3] N. Troldborg, C. Bak, H. Aa. Madsen, W. Skrzypinski *DANAERO MW: Final Report* DTU Wind Energy E-0027, April 2013
[4] C. Bak, H. Aa. Madsen N. Troldborg M. Gaunaa, W. Skrzypinski A. Fischer, U.S. Paulsen, R. Moller, P. Hansen, M. Rasmussen, P. Fuglsang *Danaero MW Instrumentation of the NM80 turbine and meteorology mast at Tjaereborg*, DTU Wind Energy report I-0083, May 2013

Additional information can be found from the following AVATAR deliverables:
[5] H.Aa.Madsen, Joachim Heinz, S. Voutsinas, N. R. García, G.Pirrung, Niels N. Sørensen, N. Troldborg *Aerodynamics of Large Rotors, Validation of advanced models against measured data* AVATAR Deliverable 4.2, August 2016

[6] N. N. Sørensen, N. Ramos García, S. Voutsinas, E. Jost, T. Lutz *Effects of complex inflow for the AVATAR reference rotor,* Deliverable D.2.6, September 2017

## *ANNEX 1 – Airfoil Contours Definition for 2D CFD Calculations*

For participants that are using CFD calculations (or possibly XFOIL or a similar flow solver) in their Wind Turbine Noise code, the airfoil contours along the blade span are provided on the share website at the following link:

https://share.dtu.dk/sites/IEA-Task-29_293350/IEA%20task%2039%20%20acoustics/Forms/AllItems.aspx

Alternatively, if the participant does not have access to this website, the data can be provided by requesting them to the contact person for the present benchmark (Email: frba@dtu.dk).

# ANNEX 7

# IEA Wind Task 39 – Quiet Wind Turbine Technology

# NOISE EMITTED OF AEROFOIL WITH SERRATED TRAILING EDGE (Proposal)

## Benchmarking experiment

Contributors: Andreas Fischer (DTU Wind Energy, DK, Contact person, Email: asfi@dtu.dk, many more

### *Introduction*

Trailing edge serrations are used in the wind energy industry to decrease the noise emission of wind turbines. However, state of the art noise prediction codes often fail to predict the effects of trailing edge serrations on the noise emission. Therefore wind turbine manufacturers design trailing edge serrations for wind turbines in an expensive trial and error process. There is a need to improve the prediction codes in order to be able to integrate them in the design process of serrations and decrease the amount of testing.
The aim of this benchmark exercise is to create high quality and publicly available wind tunnel data set for noise measurements on an aerofoil with serrated trailing edge and benchmark the existing noise prediction codes. The wind tunnel data set will help to improve the noise prediction codes.

### *1. General description of the benchmark*

The aim of this benchmark exercise is to create high quality and publicly available wind tunnel data set for noise measurements on an aerofoil with serrated trailing edge and benchmark the existing noise prediction codes. The wind tunnel data set will help to improve the noise prediction codes.
The tasks are:

- Design of serrations for a NACA63018 aerofoil, 900 mm chord. Target Reynolds number 3 to 5 million.
- Development of test matrix for wind tunnel test and benchmarking
- Test of the NACA63018 aerofoil and acoustic measurements in the Poul la Cour Wind tunnel
- Benchmarking of the serration noise codes with the wind tunnel data

### *2. Poul La Cour Wind tunnel and NACA63018 model*

The Poul La Cour wind tunnel is a Danish national research facility dedicated to testing aerofoil sections for wind turbines aerodynamically and acoustically. It was inaugurated in April 2018. The test section is surrounded by an anechoic chamber, figure 1.

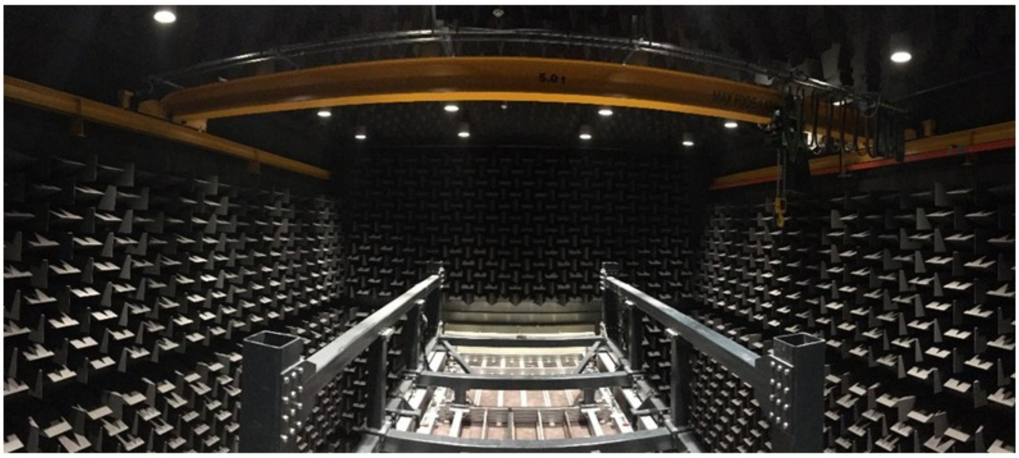

**Figure 1 – Top view on test section of the Poul La Cour wind tunnel**

In the acoustic setup the test section has Kevlar walls similar to the Virginia Tech wind tunnel [1]. The cross section of the test section is 2 x 3 m and it is 9 m long. The maximum flow speed is 105 m/s, but in acoustic configuration it can only go up to 82 m/s. The noise emitted from the aerofoil is measured by an acoustic array placed outside the test section in the anechoic chamber, figure 2.

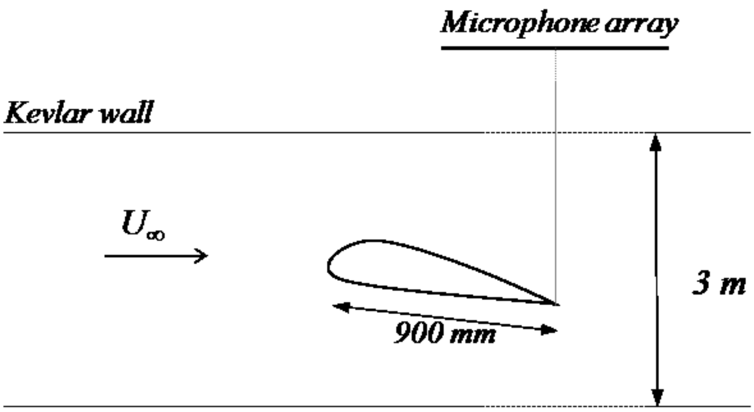


**Figure 2 - The wind tunnel setup**

The maximum Reynolds number based on a 900 mm chord length is about 5 million. The turbulence intensity in the test section is below 0.1%. The background noise level in the anechoic chamber is below 70 dB for a flow speed of 60 m/s.
The NACA 63018 wind tunnel model has a chord length of 900 mm and a span of 2m, figure 3. It is machined from aluminum and has a very high geometric accuracy (maximum surface deviation ± 0.2 mm). There are 192 pressure tabs to monitor the surface pressure at several spanwise locations.

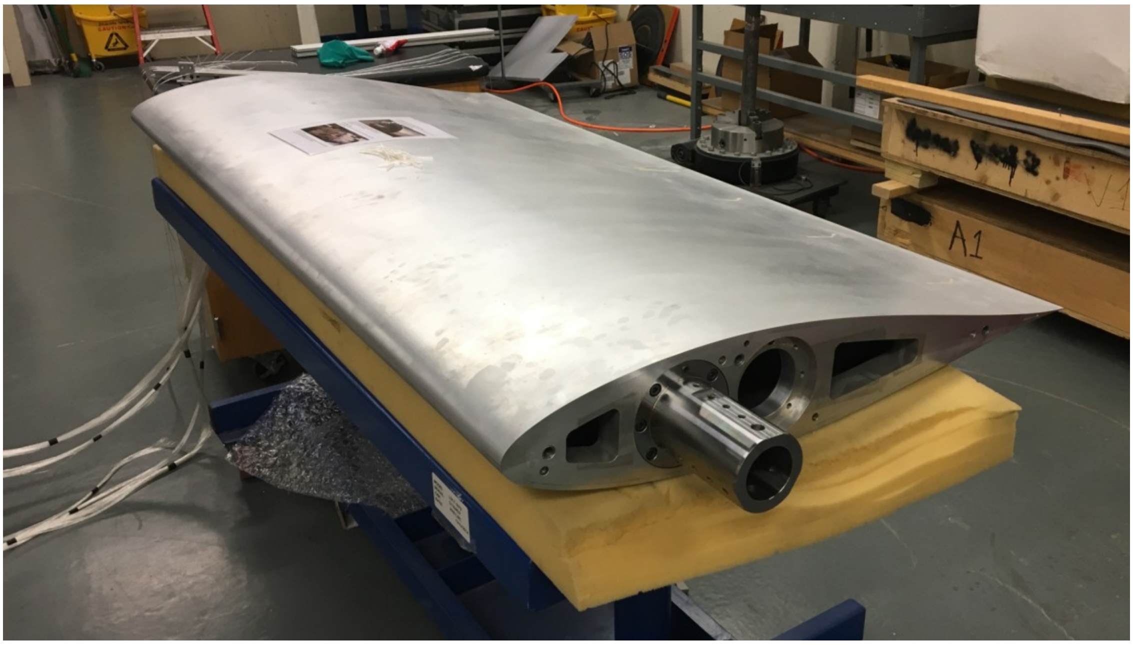

**Figure 3 - The NACA 63018 wind tunnel model**

## *3. Results to provide for the benchmarking*

In the design phase the participants are encouraged to contribute to the design of the serrations. The geometry of the serrations will be sawtooth type, figure 4.

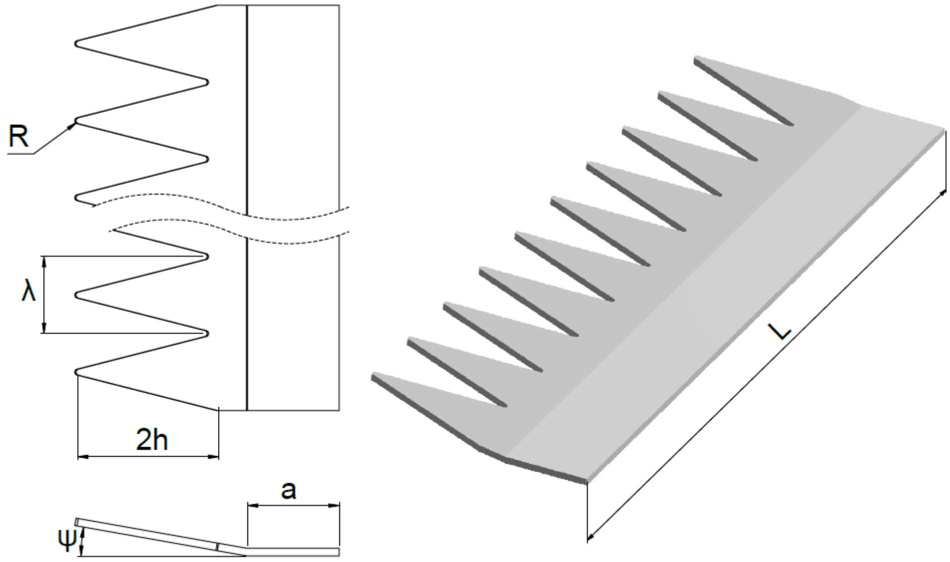


**Figure 4 - Serration geometry and design parameters**

The design parameters are the wavelength λ, the height h, the rounding of the tip R, the inclination angle ψ as well as the angle of attack of the aerofoil for which the serration should be most efficient. The target Reynolds number is 3 to 5 million. The participants are also encouraged to make suggestions to the measurement matrix.

After the experiment has been conducted the participants are supposed to provide surface pressure distributions on the aerofoil, boundary and displacement thickness at 99% chord and noise predictions for an observer position located in the center of the array. A more detailed definition will be provided after the experiment has been conducted.

### *4. Timeline*

The design process of the serration starts in April. There will be one month to finalise the design and one month for manufacturing. The experiments will be conducted in July. At this early stage the time for the wind tunnel test is still quite uncertain. The exact experimental conditions and the results will be provided two weeks after the test. Benchmark computations should be delivered two month after receiving the information about the experiment. An evaluation of the results will be presented at the end of the year in a workshop.

## References

[1] Devenport et al., The Kevlar-walled anechoic wind tunnel, Journal of Sound and Vibration, 332 (2013) 3971-3991.