Final report

1. Project details

Project title	Accelerate and increase quality in aerodynamic and aeroacoustic design loops (AeroLoop)
File no.	64018-0144
Name of the funding scheme	EUDP-2018-I
Project managing company / institution	DTU Wind Energy
CVR number (central business register)	30060946
Project partners	Vestas, Siemens Gamesa, LM Wind Power, Suzlon
Submission date	03 February 2022

2. Summary

English: The AeroLoop project focused on the development and the features of the Danish Aerodynamic and Acoustic Wind Tunnel, the Poul la Cour Tunnel (PLCT). One of four objectives were to develop ”high quality measurements”. The results were the following:

- A system to measure transition from laminar to turbulent flow has been implemented and tested successfully
- Proof of concept measurements of a lidar setup to enable flow measurements were carried out and a permanent setup has been designed.
- A system to carry out dynamic tests has been implemented and tested successfully
- Cost efficient manufacture of wind tunnel models has been developed and methods to fit existing models into PLCT has been developed successfully.
- An automated setup for the digital twin of the 3D PLCT was developed successfully
- Standard procedures were established for preparation, execution and post processing of wind tunnel tests.

The second objective was to ”benchmark the wind tunnel measurements”. It can be concluded that the measurements carried out in PLCT in general compares very well to other high quality wind tunnels.

The third objective was to ”accelerate the wind tunnel measurements”. In this context standard procedures were established to ensure a high quality, that at the same time ensures a short turnaround cycle.

The fourth and last objective was to ”improve airfoils”. Results from a total of around 100 days of wind tunnel tests are available. Most of the tests were made bilateral, but one wind tunnel campaign about leading edge roughness was made in common.

During the project and due to the development in the AeroLoop project, the wind tunnel witnessed an increasing interest from wind turbine companies outside the consortium. This supported the important purpose of the wind tunnel to use it as an enabler for wind energy research and development and shorten the time to market. Therefore, the wind tunnel contributes to the realisation of wind energy as a mean to reduce the CO2 emission.

The outcome of the project was significant and PLCT can now offer high quality measurements with a short turnaround cycle.

Dansk: AeroLoop-projektet fokuserede på udviklingen og funktionerne i den danske aerodynamiske og akustiske vindtunnel, Poul la Cour Tunnelen (PLCT). Et af fire formål var at udvikle ”højkvalitetsmålinger”. Resultaterne var følgende:

- Et system til måling af omslag fra laminar til turbulent strømning er blevet implementeret og testet med succes
- Proof-of-concept-målinger af et lidar-setup for at muliggøre flowmålinger blev udført, og der er udarbejdet et design af en permanent opsætning.
- Et system til at udføre dynamiske test er blevet implementeret og testet med succes
- Omkostningseffektiv fremstilling af vindtunnelmodeller er blevet udviklet, og metoder til at tilpasse eksisterende modeller i PLCT er blevet udviklet med succes.
- En automatiseret opsætning til den digitale tvilling af 3D PLCT blev udviklet med succes
- Der blev etableret standardprocedurer for forberedelse, udførelse og efterbehandling af vindtunnelforsøg.

Det andet mål var at ”benchmarke vindtunnelmålingerne”. Det kan konkluderes, at målingerne udført i PLCT generelt er i meget god overensstemmelse med andre vindtunneller af høj kvalitet.

Det tredje mål var at ”accelerere vindtunnelmålingerne”. I denne sammenhæng blev der etableret standardprocedurer for at sikre en høj kvalitet, men samtidig med en høj afviklingshastighed.

Det fjerde og sidste mål var at "forbedre vingeprofiler". Resultater fra i alt omkring 100 dages vindtunneltest er tilgængelige. De fleste af testene blev lavet bilateralt, men en vindtunnelkampagne om forkantsruhed blev lavet som en fælles indsats.

I løbet af projektet og på grund af den udvikling, der blev lavet i AeroLoop-projektet, oplevede vindtunnelen en stigende interesse fra vindmøllevirksomheder uden for konsortiet. Dette understøttede vindtunnelens vigtige formål om at bruge den som en katalysator for forskning og udvikling af vindenergi og forkorte ”time to market”.

Resultatet af projektet var signifikant, og PLCT kan nu tilbyde højkvalitetsmålinger med en høj afviklingshastighed.

3. Project objectives

The AeroLoop project focused on the development and the features of the Danish Aerodynamic and Acoustic Wind Tunnel, the Poul la Cour Tunnel and had four objectives:

1. High quality measurements by offering a wind tunnel with a professional service level with unique measurement capabilities.
2. Accelerated wind tunnel measurements that meet the highest demands of the wind industry by shortening the turnaround cycles substantially with standardized and automated processes decreasing the time for each design loop and thereby the time to market for new components.
3. Benchmarked wind tunnel measurements by comparing to several other wind tunnels and thereby kick start the wind tunnel by adding many years of experience to the wind tunnel.
4. Improved airfoils for each of the wind turbine manufacturer partners in terms of increased aerodynamic and aeroacoustic performance.

In the project, the performance of the wind tunnel was increased by developing and implementing techniques for measurements of transition from laminar to turbulent flow, developing and designing a setup of lidar measurements of the wake, developing and implementing a setup for dynamic stall tests, develop methods for fast and low cost manufacturing of blade sections and develop a digital twin of the wind tunnel. Furthermore, to demonstrate the performance of the wind tunnel aerodynamic and aeroacoustic benchmark tests were carried out comparing the tests in PLCT with other wind tunnels. Finally, products from each of the industrial partners were tested to characterize and develop their products further within aerodynamics and aeroacoustics in general, aerodynamic and aeroacoustic add-ons, leading edge erosion and protection and dynamic stall mechanisms.

4. Project implementation

The AeroLoop project was initiated half a year after the inauguration of the airline. Establishment of the instrumentation and running in of the wind tunnel turned out to be more challenging than anticipated. In addition, a few incidents were experienced where material was torn apart thereby damaging either instruments or part of the airline. These incidents forced a pause in the wind tunnel operation, which resulted in a few delays during the project. The wind tunnel operation was also forced into a pause due to COVID19 lock down especially in 2020. This was to some extent due to a full stop of the wind tunnel operation, but mainly because the workshops manufacturing the models to be used in the wind tunnel were either closed down or could not get the material and the parts they needed. Thus, as initially foreseen the most critical risks were that the wind tunnel could not be operated either because of technical break down or because of lack of educated staff. During the project we experienced a technical break down twice, but the COVID19 pandemic was another risk that we did not foresee.

Most of the planned activities were carried out during the project even though the establishment of the instrumentation and the analysis of the wind tunnel tests were more challenging than anticipated. An example was the tests of airfoils delivered by the partners, where the first attempts of designing and manufacturing adapters resulted in test results that were not trustworthy. More effort than foreseen was put into understanding these tests and how they should be improved. However, the tests were improved and methods to design adapters have been developed.

The most significant deviation from the project plan was the development of the lidar system that was not finalized to a level with a permanent installation and default setup. Developing this system required more tests and more considerations than anticipated and together with delays in delivery and the occupancy rate of the wind tunnel a final construction and installation of the setup was not possible within the project period. However, an implementation of the lidar system will be made after the project finalization.

Apart from this and despite that several unexpected problems turned up the problems were solved and all technical milestones were reached. For the commercial milestones a video about the Poul la Cour Tunnel was made and presented in connection to the WindEurope conference and also a leaflet was made. A final technical report about the AeroLoop project describes the performance and the services provided by the wind tunnel.

5. Project results

The project had many objectives and many activities. The objectives of the project were the following:

- High quality measurements
- Benchmarked wind tunnel measurements
- Accelerated wind tunnel measurements
- Improved airfoils

Even though many tasks were challenging almost all objectives were met. Only the lidar setup was not finalized at a level as set out at the start. A permanent setup was not obtained, but a design was made where some components were constructed. In the following the results obtained in the project are described.

5.1 High quality measurements

5.1.1 Measurements of transition from laminar to turbulent flow

An infrared thermographic camera was implemented and preliminary tests were performed. Image perspective correction and calibration tools, and transition and separation detection tools were developed. They were verified by the aerodynamic characteristics of the airfoil model by comparing with other measurements.

In Figure 1 the installation of the thermographic camera in the wind tunnel is seen. Top right an overview of the test section is shown. To the left the thermographic camera outside the test section is shown and bottom right the view of the airfoil from the camera is illustrated.

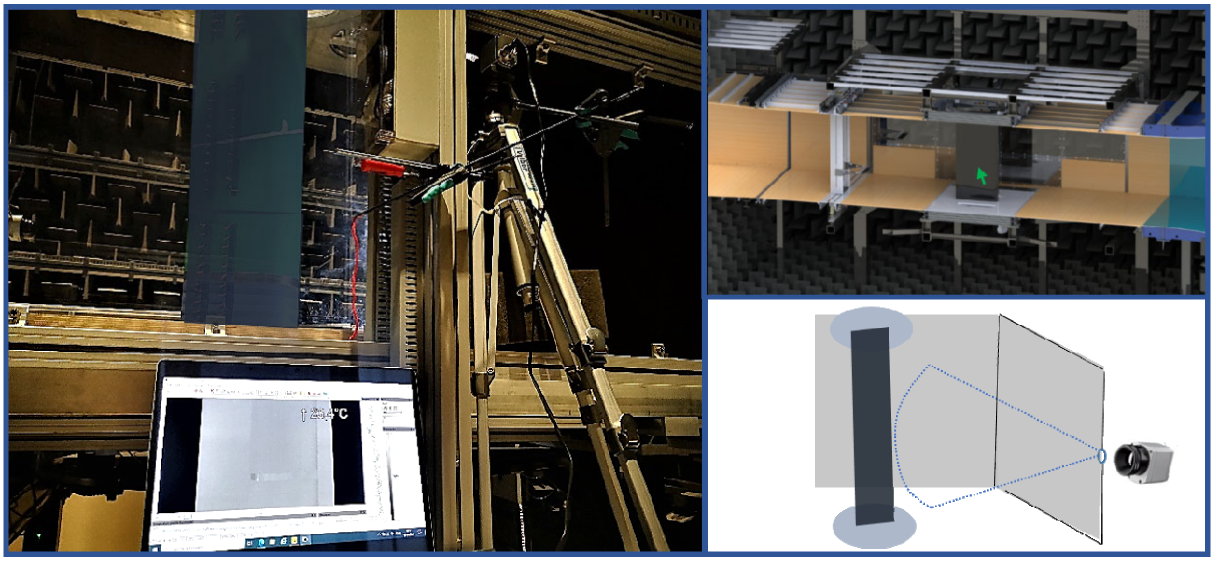

Figure 1 Installation of the thermographic camera in the wind tunnel.

In Figure 2 examples of detection of transition from laminar to turbulent flow and separation lines are seen.

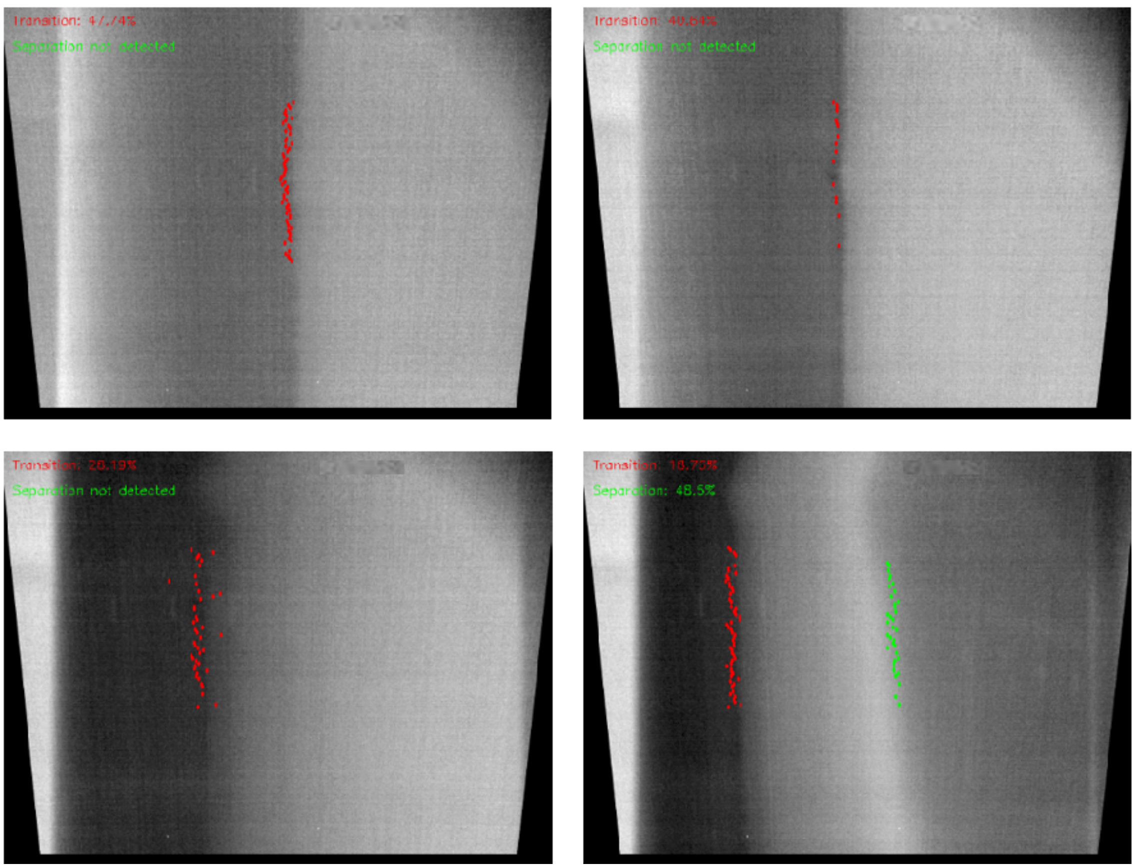

Figure 2 Detected transition (marked with a red colour) and separation (marked with a green colour) locations for various angle of attack values

5.1.2 LIDAR measurements

Use of a lidar in the Poul la Cour Tunnel (PLCT) was investigated. Several concepts for bringing in the lidar laser light into the wind tunnel where analyzed and evaluated theoretically as well as experimentally and a concept based on having the lidar telescope on a pan-and-tilt head in an aerodynamically shaped pod in the ceiling of the tunnel downstream of the test section was selected and designed. Further to this, the capability of the lidar to measure the airfoil wake was successfully demonstrated in a proof of concept campaign in the wind tunnel. The lidar measurements were in good agreement with the wake rake measurements as well as with simulations using the digital twin of the wind tunnel and the lidar sampling characteristics. The potential of using the lidar is big where the wake and thereby the drag of a model should be measured without a noisy wake rake. Furthermore, the lidar can measure, in details, the overall flow around the model.

Figure 3 shows the setup in connection to a proof of concept investigation. To the left is seen how the laser beam entered through a hole in the wall and to the right is seen how the lidar points toward the hole in the test section wall.

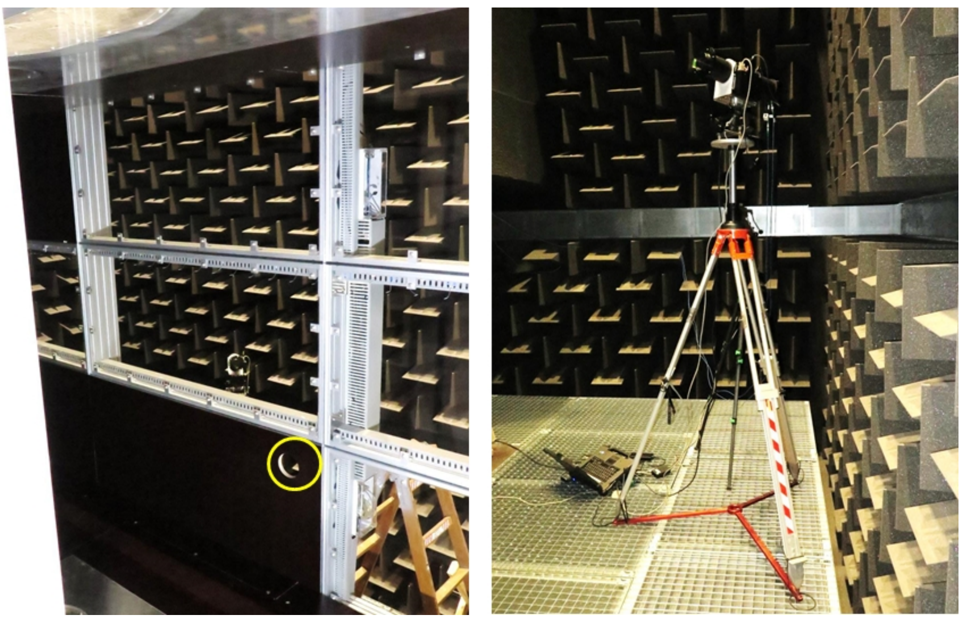

Figure 3 Lidar setup in connection to a proof of concept investigation

Figure 4 shows how the lidar in the proof of concept setup is connected to a pan-and-tilt mechanism.

Figure 4 The 3” lidar telescope can be steered by a pan and tilt head

Figure 5 shows a drawing of the final design of the pod that protects the lidar setup (lidar and pan-and-tilt head). In the front of the pod there is window that the laser beam can pass through. Figure 6 shows how the flow passes by the pod and that generated vortices are limited.

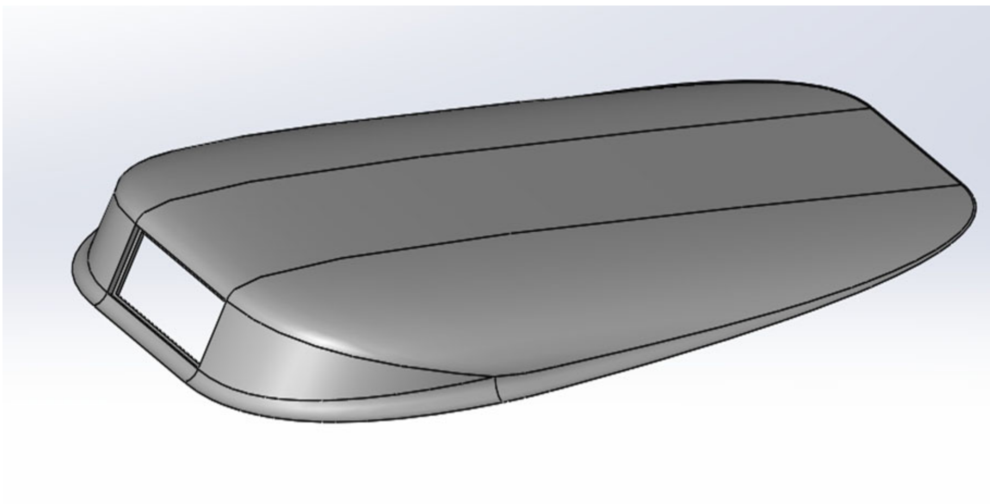

Figure 5 The pod that encloses the lidar setup to be mounted at the roof of the test section

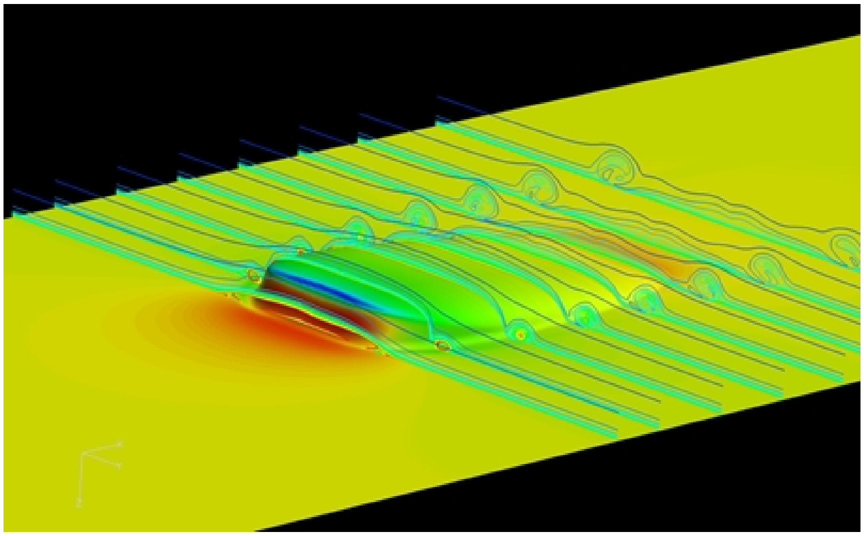

Figure 6 The vorticity in the flow around the pod. The air flows from left to right

5.1.3 Dynamic stall tests

The turntable arrangement in PLCT has been developed for dynamic stall measurement using harmonic pitching. No additional handling or setup is required for harmonic pitch testing to be carried out. The maximum achievable pitchrate is currently ∼12deg/s, which does allow for testing at relevant reduced frequencies.

Figure 7 shows the turntable from the top including the essential components. Figure 8 shows a snapshot of successful results from a dynamic stall test on an airfoil.

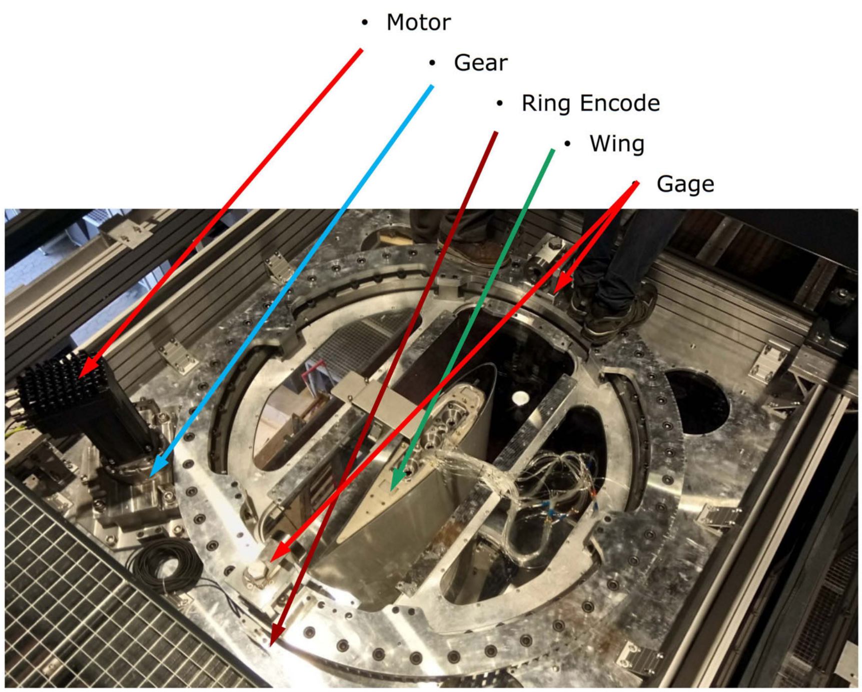

Figure 7 The turntable seen from the top with indications of where to find the motor, the gear, the ring encoder, the wing and the gage.

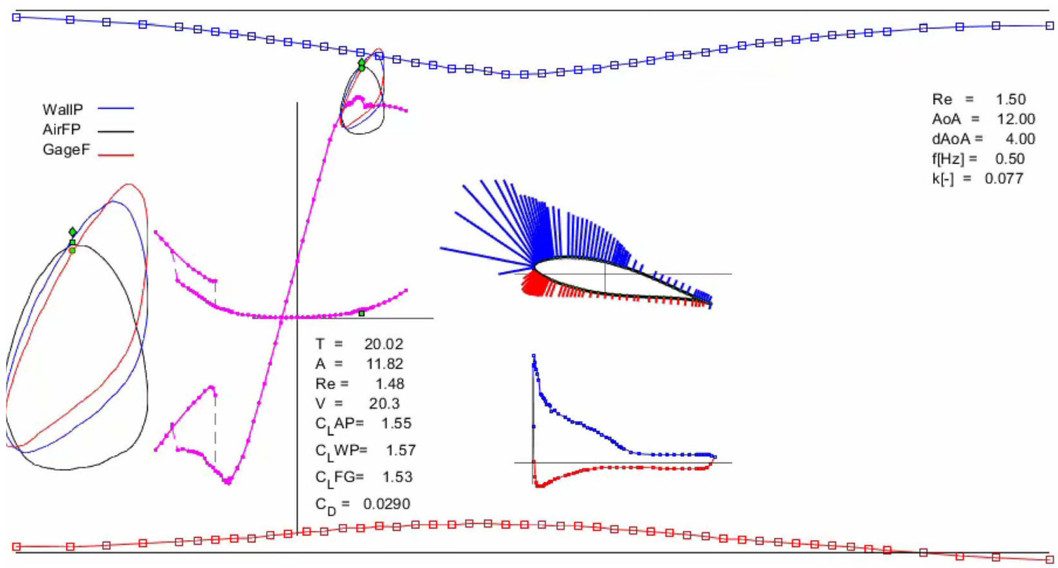

Figure 8 A snapshot of a dynamic stall loop where the airfoil is mounted in between two walls (top corresponds to south and bottom corresponds to north). The pressure distributions along the walls and on the airfoil are shown. Also, the green points indicate at which angle of attack the snapshot shows and compared to steady state lift and drag.

5.1.4 Methods for fast and low cost manufacturing of blade sections

The cost analysis of a wind tunnel campaign including the data analysis showed that the savings by using a cheap model were 10% if the model was fully instrumented (i.e. with pressure orifices) and 25% if the model was not instrumented. It might be beneficial to use a low cost model, if the test campaign is short and indicative results are sufficient. The investigation of a low cost manufacturing processes led to a procedure to manufacture cost efficient and high quality airfoil extensions for existing models that were used in other wind tunnels. The extension of existing models was in high demand by the industrial project partners, because it reduced the costs of the wind tunnel tests and enabled facility cross validation.

Figure 9 shows a new method of how to use airfoils tested in other wind tunnels in PLCT. Thus, a beam is attached to the existing airfoil and around this beam an airfoil shaped surface will be mounted.

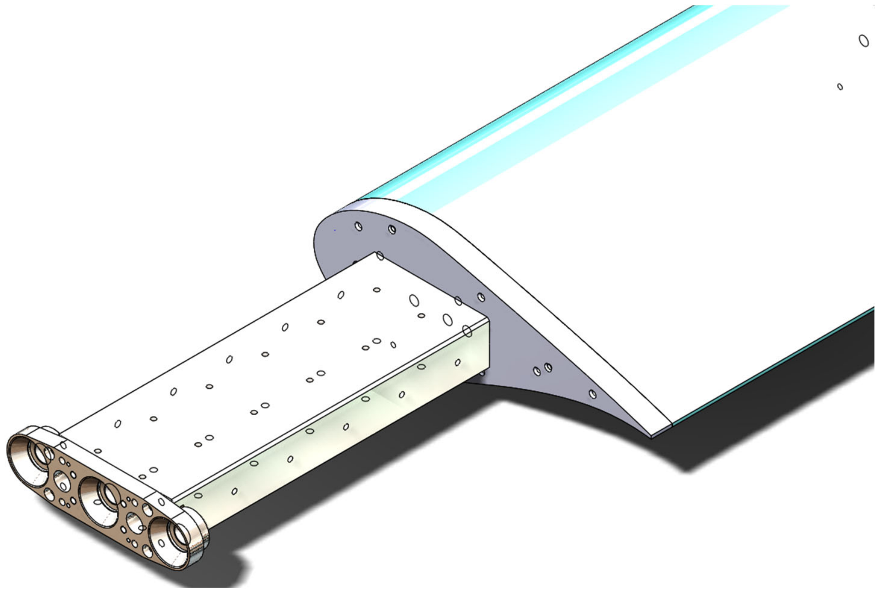

Figure 9 A beam connected to an existing airfoil to connect to the turntable in the test section. An airfoil shaped body-work will be mounted on the beam.

5.1.5 Digital twin of the wind tunnel

An automated setup for the digital twin of the 3D PLCT was developed, using the DTU in-house flow solver EllipSys3D. The digital twin was used to investigate overall tunnel performance, test section speed as function of pressure gradient, and the tunnel effects on the airfoil performance. The digital twin is showing potential in exploring e.g. lidar setup and is generally proven valuable in understanding the details of the flow in the tunnel.

Figure 10 shows the computational grid required to predict the flow in the test section with Computational Fluid Dynamics (CFD). The air flows from left to right and the contraction is seen to the left (in red) accelerating the flow into the test section. The flow passes by the airfoil model and exits the test section into the diffuser (in green).

Figure 11 shows a top view of the test section and how the model is part of a cylindrical grid that can be exchanged depending on the model to be investigated.

Figure 12 shows axial velocities computed with the same grid and how the velocities increase over the upper side and decrease under the lower side. The increased velocities creates the suction on the upper side that results in a lift.

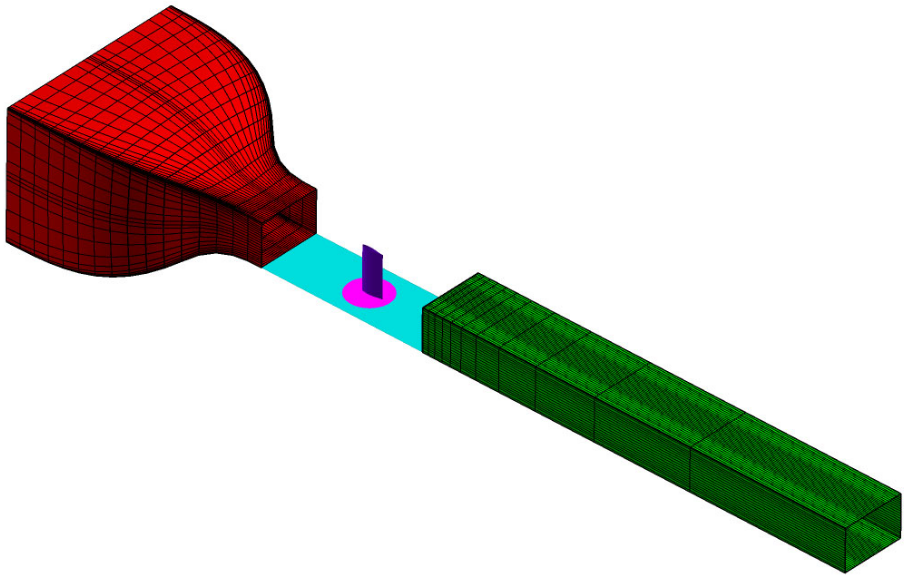

Figure 10 Setup of the computational grid in the digital twin.

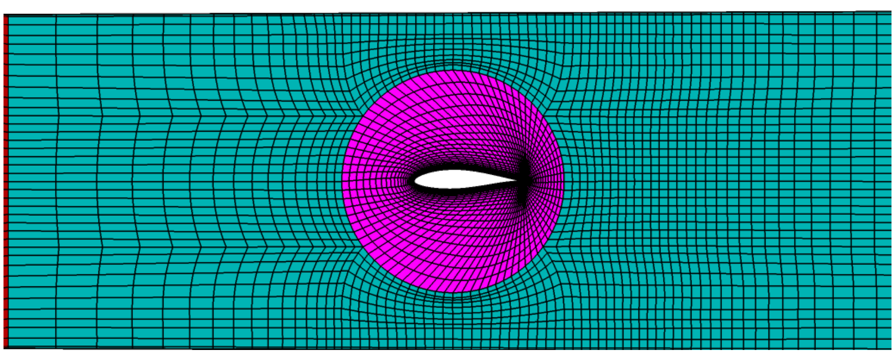

Figure 11 The grid seen from the top. This indicates that the circular part can be exchanged in the digital twin when different airfoils should be tested in the setup.

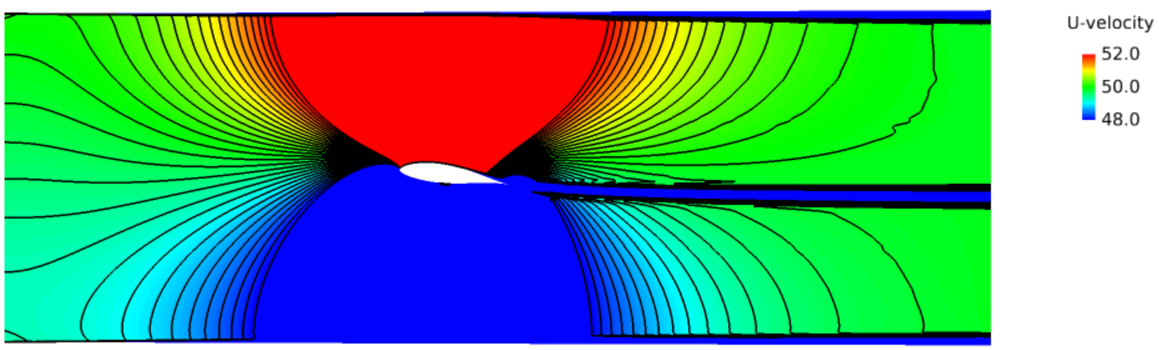

Figure 12 Computed axial velocities around an airfoil from the digital twin

5.1.6 Standard procedures

Standard procedures were established such as design of airfoils and adapters for airfoils and check of the quality of the airfoils before tests, mounting of zigzag tape and aerodynamic and aeroacoustic add-ons, in the analysis of the data and reporting of data.

5.2 Benchmarked wind tunnel measurements

The measurements carried out in PLCT compares well to other high quality wind tunnels. Dis-agreements between measurements have been observed, but for the aerodynamic tests, this is for angles of attack where separation appears and are therefore likely due to 3D effects and commonly seen when comparing wind tunnels. The comparison for the thinner airfoil is in general very good, but the thicker the airfoils are the bigger the deviations get. This is not attributed to PLCT, but is a general issue for all wind tunnels.

Figure 13 shows the lift coefficient (c_l) as a function of the drag coefficient (c_d) (Left) and lift coefficient (c_l) as a function of angle of attack (AoA) as measured in PLCT. These data are compared to three other high quality wind tunnels: Delft University, LM Wind Power and DNW HDG. It is clear that the agreement is very good. Minor differences are seen for angles of attack between -10 and 10. Only in stall at angles of attack bigger than 10 degrees, bigger differences appear. However, this is expected because stall is a 3D phenomenon, so the results differ from wind tunnel to wind tunnel and especially depend on the aspect ratio, which is the span length relative to the chord length.

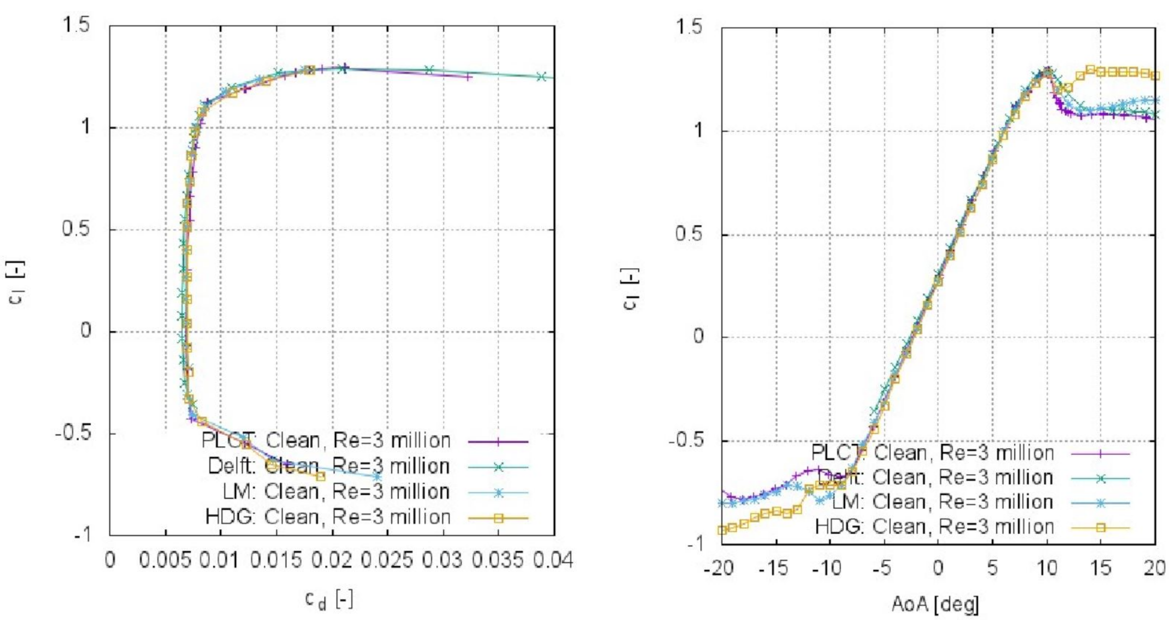

Figure 13 Left: Lift coefficient (cl) as a function of drag coefficient (cd) for the DU00-W-212 airfoil. Right: Lift coefficient (cl) as a function of angle of attack (AoA). Results from PLCT is compared to data from the Low Speed Low Turbulence Wind Tunnel at TU Delft (Delft), LM Wind Power Wind Tunnel (LM) and DNW-HDG Wind Tunnel (HDG).

5.3 Accelerated wind tunnel measurements

Standard procedures were established to ensure a high quality, that at the same time ensures a short turnaround cycle. Thus, in the design of airfoils and adapters for airfoils it was ensured that the model manufacturers got the required information as fast as possible. Also, in the execution of tests such as mounting of zigzag tape and aerodynamic and aeroacoustic add-ons was made in a standardized way to ensure that tests should not be re-done and are repeatable. In the analysis of data there were a significant effort to automate the analysis and the reporting. At the end of the project an automated setup to analyze and report has been established.

5.4 Improved airfoils

Results from in total around 100 days of wind tunnel tests are available. Most of the results are confidential and has not been published. However, results from a common wind tunnel campaign concerning leading edge roughness showed that the four industrial partners agreed on a common interest and took part in this common effort. It showed that airfoil performance degrade when zigzag tape and sandpaper was mounted, but also showed that the performance did not degrade in the same way whether zigzag tape or sandpaper was used. Many more results and conclusions were made for each partner.

Figure 14 shows the lift coefficient (c_l) as a function of the drag coefficient (c_d) (left) and lift coefficient (c_l) as a function of angle of attack (AoA) as measured in PLCT (right). An airfoil with a clean surface is compared to surfaces with different types of roughness at the leading edge. The conclusion from this campaign is, e.g. that the common simulation of leading edge roughness with zigzag tape performs differently than if sandpaper is used.

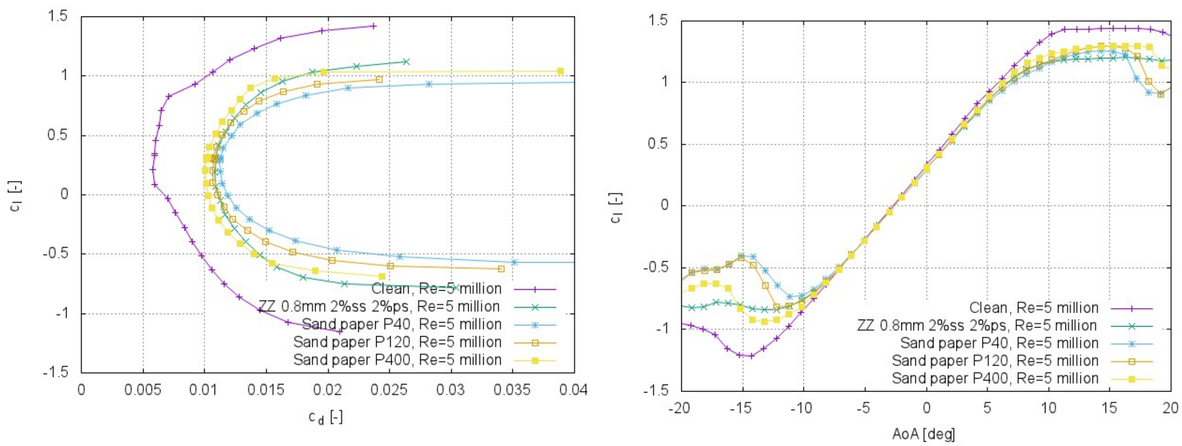

Figure 14 Left: Lift coefficient (c_l) as a function of drag coefficient (c_d) for the NACA 63_3-418 airfoil. Right: Lift coefficient (c_l) as a function of angle of attack (AoA). Tests with different types of leading edge roughness.

5.5 Value of the wind tunnel

The wind tunnel was extensively used during the project period. Especially in the last year many wind tunnel tests were carried out, which was partly due to the COVID19 situation where many activities were queueing because of delays, but also because wind tunnel tests in other projects. In some cases the users of the wind tunnel did not use the new features in the wind tunnel directly, but especially the transition detection was often used. In addition, the experience obtained for the model manufacturing made the preparation easier and faster. The knowledge of the digital twin made the user aware that further help in the analysis was available even though it was not used by the users. However, it was used by DTU when analysis of certain experiments were challenging.

Several new things were learned. One of the non-technical learnings in the wind tunnel was about pricing. One way of pricing is to pay per day, but another is to pay per test of model configuration. Some partners could see a benefit of offering both and therefore this is considered by PLCT.

5.6 Dissemination

Potential users of PLCT are aerodynamicists from the wind energy industry. They will often be updated at wind energy conferences and journals dedicated wind energy. Much of the dissemination is therefore directed to the wind energy specific Torque conference, but also presented on conferences directed to the industry, e.g. within operation and maintenance and blade design and manufacture. Further to this, the wind tunnel has also been presented at more general conferences such as the Wind Europe conference, where all kinds of wind energy related products and services are presented. In connection to this a movie about PLCT was made (https://windeurope.org/windflix/videos/interview-with-christian-bak-ozge-sinem-ozcakmak-oliver-lyllof-dtu/) and further dissemination based on this (https://www.youtube.com/watch?v=qXjZwOp2i6I and https://m.facebook.com/watch/?v=482461229827259&_rdr).

Publications and presentations have been given during the project period:

- Olsen AS, Sørensen NN, Bak C, Gaunaa M, Mikkelsen R, Fischer A et al. Why is the measured maximum lift in wind tunnels dependent on the measurement method? Journal of Physics: Conference Series. 2020;1618(3). 032040. https://doi.org/10.1088/1742-6596/1618/3/032040
- Sørensen NN, Olsen AS, Bak C, Gaunaa M, Beckerlee JS, Fischer A et al. CFD modeling of the Poul la Cour Tunnel. Journal of Physics: Conference Series. 2020;1618(5). 052047. https://doi.org/10.1088/1742-6596/1618/5/052047
- Sjöholm M, Pathan S, Ildvedsen S, Beckerlee J, Fischer A, Mikkelsen R, Mann J, Bak C, Lidar developments for remote wind sensing in an aeroacoustic wind tunnel, WESC2021, 25-28 May 2021, Web conference from Hannover
- Mikkelsen R , Bak C, Gaunaa M, Fischer A, Olsen AS, Ildvedsen S, Beckerlee J, High Reynolds number dynamic stall testing of a harmonic pitching NACA 63-418 aerofoil, WESC2021, 25-28 May 2021, Web conference from Hannover
- Grasso F, Bak C, Olsen AS, Ravnkilde L, Johansen RK, Leading Edge Protection Impact on Airfoil Performance: An Experimental Investigation, AIAA 2022-0277, AIAA SCITECH 2022 Forum, January 3-7, 2022, San Diego, CA & Virtual, https://doi.org/10.2514/6.2022-0277
- Bak C, Olsen AS, Fischer A, Lylloff O, Mikkelsen R, Gaunaa M, Beckerlee J, Ildvedsen S, Vronsky T, Grasso F, Löven A, Brorsma L, Akay B, Madsen J, Hansen R, Kommer R, Wind tunnel benchmark tests of airfoils, To be presented at the conference Torque 2022, 1-3 June Delft
- Ed. Bak C, Development of tests in the Poul la Cour Tunnel. AeroLoop: Final report, DTU Wind Energy Report E-023, ISBN: 978-87-87335-59-1, January 2022

6. Utilisation of project results

The increased performance of the wind tunnel obtained through the development of transition measurements, setup with lidar, dynamic stall, airfoil manufacturing methods and digital twin will together with the benchmarking and the experience gained through the wind tunnel tests carried out for the industrial partners, be used in future wind tunnel tests in wind energy development and research. The starting point for the project was a very good airline and basic instrumentation, but the AeroLoop project has ensured that more advanced measurement methods and the workflow has been optimized so that industrial tests can be carried out with a short turnaround cycle. The target groups for the tests are wind turbine blade designers and those within operation & maintenance of wind turbines with focus on aerodynamic and aeroacoustic characterization of airfoils/blade sections. However, tests can also be carried out for others, such as wind turbine tower designers and wind farm planners.

During the project the partners tested their products and also got the possibility to test the quality and the workflow in the wind tunnel. This process was very valuable because the partners could make their requirements clear and procedures in the wind tunnel could be accommodated to this.

Also, tests were carried out for the partners, where the workflow was tested, the equipment, the procedures and the communication with the client. The purpose is to carry out high quality tests with a short turnaround cycle to ensure that the development and research can be carried out fast and trustworthy. Thus, the wind tunnel tests is an enabler for wind energy research and development to shorten the time to market and ultimately decrease the cost of energy for wind turbines.

Especially in 2021 a positive balance between income and expenses was experienced so the business case for the wind tunnel was satisfactory. Also, several tests were carried out with the purpose of either designing a new generation of rotors or updating existing rotors. Thus, as set out originally in the description of the AeroLoop project the tests in the wind tunnel enabled the possibility to reduce time to market for the wind turbine manufacturers.

Three of the four objectives in the project related to the wind tunnel, where high quality, short turnaround cycles and benchmarking were obtained. However, a fourth important objective was to improve the products for the partners. Here, both aerodynamic and aeroacoustic measurements were carried out to characterize and document the performance. The results from these tests have been used to compare the performance of PLCT further, to provide documentation of how devices on blade sections performed, to investigate brand new concepts etc. Thus, the results from the wind tunnel have been used directly in new blade designs. In this way, the tests have either ensured an increased certainty or provided data for their products that could not be provided elsewhere because of the high Reynolds numbers or the aeroacoustic features of the PLCT.

Other wind tunnels exist and many wind turbine manufacturers already use those. Because of the bigger size PLCT is slightly more costly and therefore it is important that an advantage of using PLCT instead of others is clear. There has been focus on this fact in the project. That is the reason that after the project, dissemination of the performance of the wind tunnel will continue and focus will be on the further development of the uniqueness that is the size and high flow speeds (and thereby the Reynolds numbers), the acoustic features and the short turnaround cycles. However, no other wind tunnels in the world can test at these high Reynolds numbers and at the same time with the aeroacoustic feature and the short turnaround cycles.

Wind tunnel tests in PLCT provides documentation of the aerodynamic and aeroacoustic performance of wind turbine components and ensure that data can be provided in a reliable and fast manner. This again ensures better performance and shorter time to market and thereby lower cost of energy. Therefore, the wind tunnel contributes to the realisation of the energy policy objectives, where wind energy should take a bigger share of the energy system and thereby reduce the CO2 emission.

7. Project conclusion and perspective

The objectives of the project were to deliver the following after the project:

- High quality measurements
- Benchmarked wind tunnel measurements
- Accelerated wind tunnel measurements
- Improved airfoils

Even though many tasks were challenging almost all objectives were met.

Concerning the objective about "high quality measurements" we can conclude the following:

- An infrared thermographic camera was implemented and preliminary tests were performed. Image perspective correction and calibration tools, and transition and separation detection tools were developed. They were verified by the aerodynamic characteristics of the airfoil model by comparing with other measurements.
- Use of a lidar in the Poul la Cour Tunnel was investigated. Several concepts for bringing in the lidar laser light into the wind tunnel where analyzed and evaluated theoretically as well as experimentally and a concept based on having the lidar telescope on a pan-and-tilt head in an aerodynamically shaped pod in the ceiling of the tunnel downstream of the test section was selected and designed. Further to this, the capability of the lidar to measure the airfoil wake was successfully demonstrated in a proof of concept campaign in the wind tunnel. The lidar measurements were in good agreement with the wake rake measurements as well as with simulations using the digital twin of the wind tunnel and the lidar sampling characteristics. The potential of using the lidar is big where the wake and thereby the drag of a model should be measured without a noisy wake rake. Furthermore, the lidar can measure, in details, the overall flow around the model..
- The turntable arrangement at PLCT has been developed for harmonic pitching dynamic stall measurement. No additional handling or setup is required for harmonic pitch testing to be carried out. The maximum achievable pitchrate is currently 12deg/s, which does allow for testing at relevant reduced frequencies
- The cost analysis of a wind tunnel campaign including the data analysis showed that the savings by using a cheap model were 10% if the model was fully instrumented and 25% if the model was not instrumented. It might be beneficial to use a low cost model, if the test campaign is short and indicative results are sufficient. The investigation of a low cost

manufacturing processes led to a procedure to manufacture cost efficient and high quality aerofoil extensions for existing models that were used in other wind tunnels. The extension of existing models was in high demand by the industrial project partners, because it reduced the costs of the wind tunnel tests and enabled facility cross validation.
- An automated setup for the digital twin of the 3D PLCT was developed. The digital twin was used to investigate overall tunnel performance, test section speed as function of pressure gradient, and the tunnel effects on the airfoil performance. The digital twin is showing potential in exploring e.g. LIDAR setup and is generally proven valuable in understanding the details of the flow in the tunnel.
- Standard procedures were established such as design of airfoils and adapters for airfoils and check of the quality of the airfoils before tests, mounting of zigzag tape and aerodynamic and aeroacoustic add-ons, in the analysis of the data and reporting of data.

Concerning the objective about "benchmarked wind tunnel measurements" we can conclude that the measurements carried out in PLCT compares well to other high quality wind tunnels. Disagreements between measurements have been observed, but for the aerodynamic tests this is for angles of attack where separation appears and are therefore likely due to 3D effects, and commonly seen when comparing wind tunnels.. The comparison for the thinner airfoil is in general very good, but the thicker the airfoils are the bigger the deviations get. This is not attributed to PLCT, but is a general issue for all wind tunnels.

Concerning the objective about "accelerated wind tunnel measurements" standard procedures were established to ensure a high quality but in the same time with a short turn around cycle. Thus, in the design of airfoils and adapters for airfoils it was ensured that the model manufacturers got the required information as fast as possible. Also, in the execution of tests such as mounting of zigzag tape and aerodynamic and aeroacoustic add-ons was made in a standardized way to ensure that tests should not be re-done. In the analysis of data there were a significant effort to automate the analysis and the reporting. At the end of the project an automated setup to analyse and report has been established.

Concerning the objective about "improved airfoils" results from in total around 100 days of wind tunnel tests are available. Most of the results are confidential and has not been published. However, because the aerodynamic performance of airfoils with leading edge roughness was an interest that all partners had, a common wind tunnel campaign was carried out. It showed that airfoil performance degrade when zigzag tape and sandpaper was mounted, but also showed that, e.g. the performance did not degrade in the same way whether zigzag tape or sandpaper was used. Many more results and conclusions were made for each partner.

There are many perspectives to the work in the wind tunnel. Concerning development of the instrumentation there is the following plan:

- For detection of transition, a setup will be made, so that transition can be measured also in the aeroacoustic setup. It will be connected to the data acquisition system in the wind tunnel, enabling an automatic and time synchronised recording of the infrared pictures. Also, the challenges of measuring transition on aluminum models with an infrared camera will be further investigated and alternative methods for transition detection will be investigated.

- For flow measurements using a lidar the pod covering the lidar instruments will be manufactured during 2022 and the acoustic noise level from the pod will be characterized. Also, a generator for weak aerosol seeding is needed in order to facilitate high signal to noise levels allowing for short sampling times. Furthermore, a great potential is that flow patterns in general can be mapped remotely in the whole test section to be used for many purposes.
- For dynamic tests the use of short tubing should be carried out in future campaigns for clarifying the extent of time-lag using the present long tubing. Also, standardization of the dynamic stall tests is important to investigate to be able to document the dynamic characteristics of airfoils for wind turbine rotors.
- Concerning manufacturing of models further investigation of optimizing the models for higher quality and lower cost will continue.
- For the digital twin the acoustic setup with the Kevlar walls will be investigated further, coupling this to experimental activities in order to provide accurate boundary conditions for representing the Kevlar walls.
- In the longer run further investments in instrumentation of the wind tunnel are needed such as Particle Image Velocimetry (PIV), an aeroelastic setup and a foundation for models mounted in the floor/ceiling.

The further perspective for the wind tunnel is to increase the value of the tests even more. The plan in the longer run is to couple the wind tunnel tests even closer to aerodynamic full-scale wind turbine measurements and the digital twin. This is to characterize products in the wind tunnel and correct the data to be used on full-scale wind turbines with very high certainty and thereby reducing the number of full-scale measurements and shorten the time to market further.

Even though the establishment of the procedures and methods in connection to the wind tunnel tests were challenging and more challenging than initially foreseen, the outcome of the AeroLoop project was significant. Even though the development of procedures, methods and measurement techniques will continue for many years, PLCT can now offer high quality measurements that has been benchmarked against other wind tunnels and this can be done with short turnaround cycles to ensure a fast implementation of wind turbine components with improved performance.