AIRTuB Final Report

Summary

Due to global environmental concerns, there is an increasing demand for sustainable energy sources, with wind turbines being currently the most popular solution, as the power per area ratio is the highest among alternatives. To push the power output the trend in the industry is increasing the length of the blades currently spawning over 100m, proportionally increasing the speed of the blade sections furthest from the rotor. Droplets and other particulates colliding at high speeds with the leading edge of the blade result in accumulating erosion events. To protect the Lead edge and minimize operational cost, a Leading Edge Protection film (LEP) is often applied. Nevertheless, the addition of LEP reduces the initial wind turbine aerodynamic performance, as it disrupts the airflow pattern, with the upside of maintaining the blade over a longer period.

The goal of WP5 in the AIRTuB project was to produce a smooth transition coating between the LEP tape and the surface on a wind turbine blade. During the project, Qlayers focused on developing a head for applying this transition coating. LM Wind Power provided 3 wind tunnel models: DU08-W-210, NACA63-621 and DTU-C21.

Within the scope of WP5, Qlayers has defined and executed the following activities:

1. Research on the pre-treatment module
2. Research on the printing method
3. Research on the automation
4. Development of a printing head for the application of the LEP transition
5. Integration of the printing head on a robotic arm
6. Production of the LEP transition for the wind tunnel testing section

Calibration measurements of the airfoils were performed in the wind tunnel of LM Wind Power (LSWT – Low Speed Wind Tunnel). After application of the transition shape by Qlayers, LM Wind Power remeasured the same airfoils, to verify the aerodynamic improvement.

Based on the wind tunnel measurements provided by LM, there is a reduction of 0.42% in Levelized Cost of Energy (LCOE) caused by the post-applied LEP towards additional chamfering. The theoretical maximum achievable LCoE is 1.16%. It can be concluded that the manufacturing method can be improved since the automated process with the robot is still too inaccurate. Also, the UV cured polymer used in this project was not the optimal match with the LEP tape. Further studies and experiments must be conducted to improve the performance of the blade with the LEP tape and transition application method.

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Introduction

In the search for more power output per installed wind turbine, the manufacturers are evolving towards the production of larger and larger wind turbine blades. The reason is that the higher the wind turbine reaches the more power the wind turbine can capture. Although larger wind turbines can generate more power output other new challenges arise, such as the structural design and manufacturing of such long blades. Furthermore, when deployed in wind farms, the tips of the wind turbines reach and surpass speeds of 90m/s- comparable to the speed of a small firearm bullet. At these speeds even raindrops or dust particles impacting the wind turbine blades create- pits at the surface of the leading edge, eroding the blade. The pitting can grow to the extent that the blade gets structurally damaged which eventually can lead up to its structural failure.

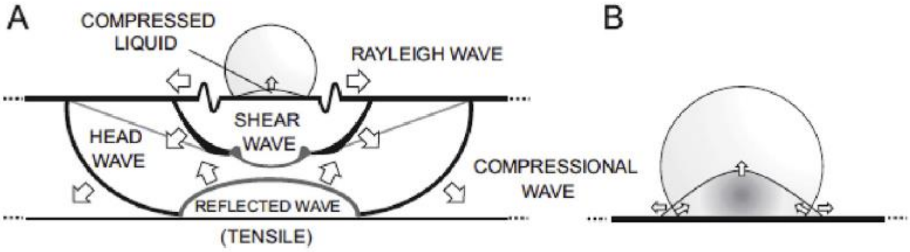


Figure 1: Effect of high-speed droplet impact.

(Reference: Gohardani O. Impact of erosion testing aspects on current and future flight conditions. Prog Aerosp Sci 2011; 47:280–303.https://doi.org/10.1016/j.paerosci.2011.04.001.)

Since this phenomenon is most severe on the leading edge some recent developments have been done to protect this area. To combat this issue Leading Edge Protection (LEP) can be added in the form of a coating or a sticker during production. The LEP has been proven to provide good durability against leading-edge erosion. From an application perspective the use of a sticker is the easiest option both in production and in the field. However, one of the challenges with the LEP sticker is the abrupt transition between the LEP and the topcoat which causes a disruption of the aerodynamic flow. To avoid this the transition should be smoothened out.

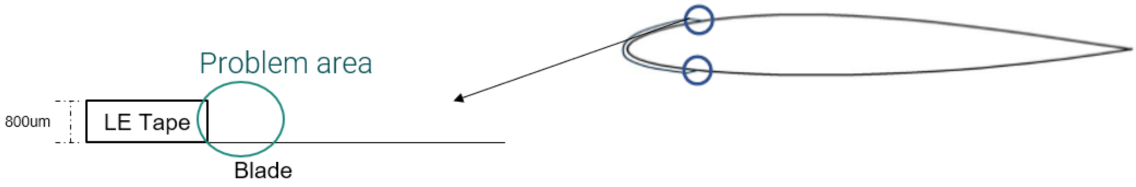


Figure 2: Close- up illustration of the problem area on the wind turbine blade.

Project Description

Objective

The objective of Qlayers' WP5 is to produce a smooth transition coating between the Leading Edge Protection (LEP) tape and the surface on a wind turbine blade. During the project, Qlayers focused on developing a head for applying this transition coating. LM Wind Power provided 3 wind tunnel blade test sections where the LEP and subsequently the transition coating was to be applied within our facility.

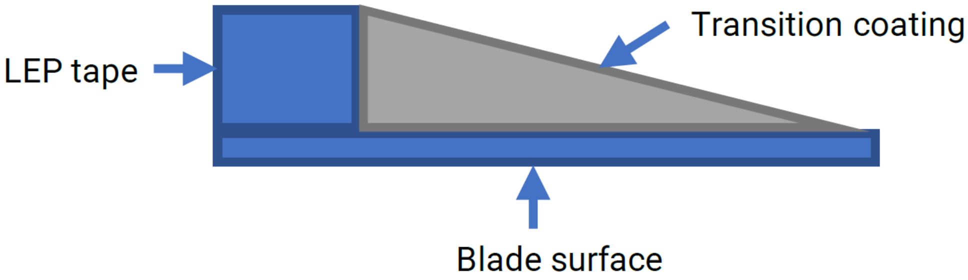
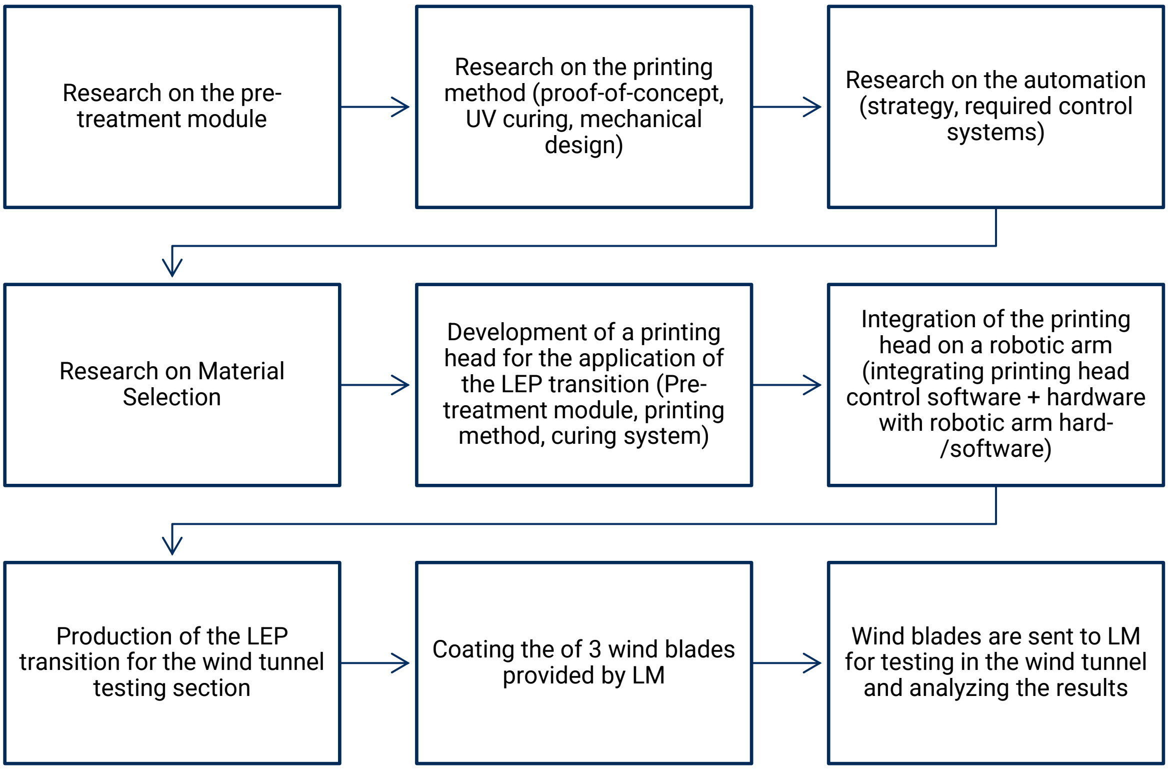


Figure 3: Diagram of the cross-sectional view of the transition coating.

Activities

The following workflow diagram summarizes the activities of WP5 of Qlayers:



For the application of coatings, the surface properties must match the applied coatings. This ensures the full performance of the coating lifetime and makes sure that the coating does not fail based on the adhesion. The surface properties can also influence the coating wettability, this is important since the transition that is desired needs to be smooth and continuous.

For the application of the coating, the process must match the coating properties. Based on what is possible with the coatings the head needed to be designed. Hence, the first part of the research focused on the conceptual design phase. The next step was to make a trade-off of the different concepts and make some physical proof-of-concept systems. The proof-of-concept tests provided the required input for the preliminary design of the printhead. Based on the performance of the coating application head, the end-effector needs to be moved according to a certain tolerance and with a certain speed with respect to the LEP transition. The head's performance was also determined the application strategy and hence the actuator's motion strategy. In this project, both a CNC system and a robotic arm were used as a platform for the actuation of the coating application head. The first step was performed by a CNC platform to test the performance of the print head. The next step was the integration of the printhead on a robotic arm for the full-integration test and final application for the wind tunnel testing section.

Once the printhead had been fully integrated with the robotic arm, the full system needed to be tested on a small object to validate that the full system was working according to specification. The next step was to perform a dry run of the robot over the wind tunnel testing section. The final step was to apply the LEP transition on the blade test sections which will be tested in the wind tunnel of LM Windpower. These tests showed the possible aerodynamic performance of making a smooth transition between the LEP and the blade’s topcoat.

Research

Different surface treatments lead to different wettability behavior. However, there is no literature on the materials used specifically on wind turbines blades and the polymers Qlayers selected to produce the transition. Therefore, the first part of the research was focused on determining the effect of different pre-treatments in combination with the materials occurring in the leading edge of the wind turbine blade and in the wind tunnel testing section.

Research on pre-treatment

The pre-treatment of the substrate on which the coating is applied is of most importance.

The primary reason for this is that it governs not just the adhesive strength of the coating on the substrate, but also the wetting behavior, which is crucial to comprehend when creating a transition as per the methodology employed in this research.

In the industry, the main pre-treatment applied before applying coatings or stickers is the cleaning of the substrate using isopropanol and a dust-free fabric. In this case, a strong mechanical bond is required, sometimes sanding is done with an extra cleaning step using isopropanol to remove the dust.

As a part of the application, it is also necessary to understand the wetting for different coatings. To have a clear reference cleaning was done with isopropanol. The coatings selected were UV curing coatings which can be cured fast using UV light. The fast curing helps in the application of the transition since it also allows multiple layers to build up on top of each other if it is necessary. The results of these tests are presented in the section on the wetting of the LEP transition without pre-treatment.

In general, there are a few main methods that are applied for the pre-treatment of surfaces:

- Mechanical treatment
- Corona treatment
- Plasma treatment

Each of these different methods will be discussed in the section on the wetting of the LEP transition with the pre-treatment.

Wetting of the LEP transition without pre-treatment

For the deposition of these coatings a normal needle and syringe were used to apply the coating on the transition and to test the wetting. Each of the samples had the same cleaning procedure to ensure that the results could be compared. Next to testing different coatings also, different amounts were tested to see the effect of the coating flowing out.

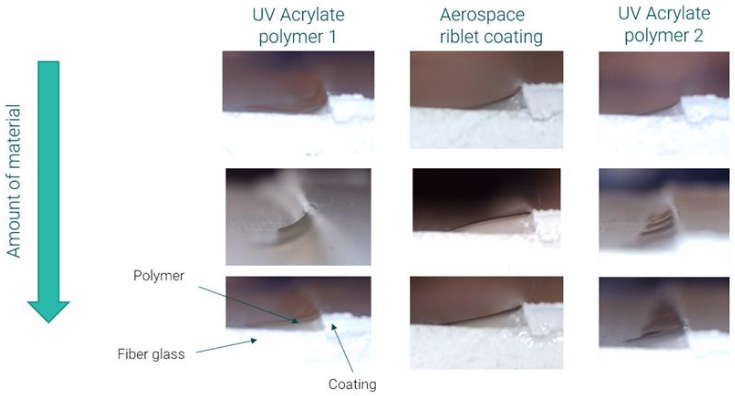


Figure 4: Wetting of the LEP to the topcoat with different UV curing polymers.

From the results, it was clear that the different coatings behaved similarly. When the coating was added in the LEP transition region the coating would change from a concave to a convex shape and back when the coating started to progress outwards. This showed the significance of the amount of material added and the instability of the process.

Wetting of the LEP transition with pre-treatment

Mechanical Treatment

The most common technique is sanding the surface. This increases the surface roughness which can allow better mechanical bounding. In general, sanding leads to a random surface roughness. However, when it is done unidirectional the wetting of the material happens in the direction of the sanding as shown in Figure 5. The tests proved that coarser sandpaper created more surface roughness which affected the wetting of the material in one direction.

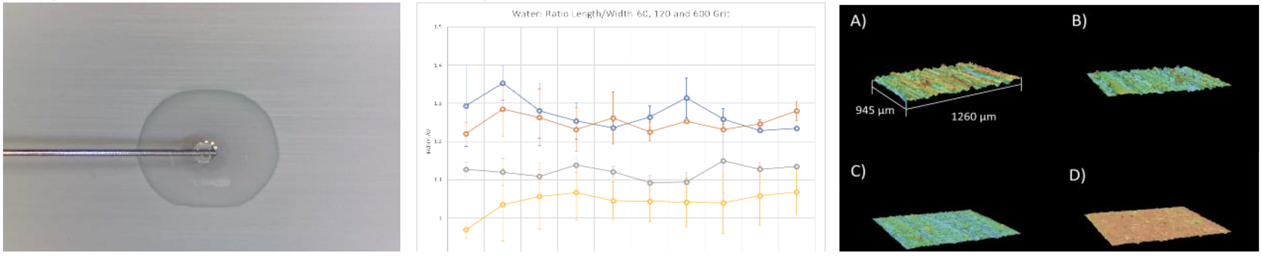
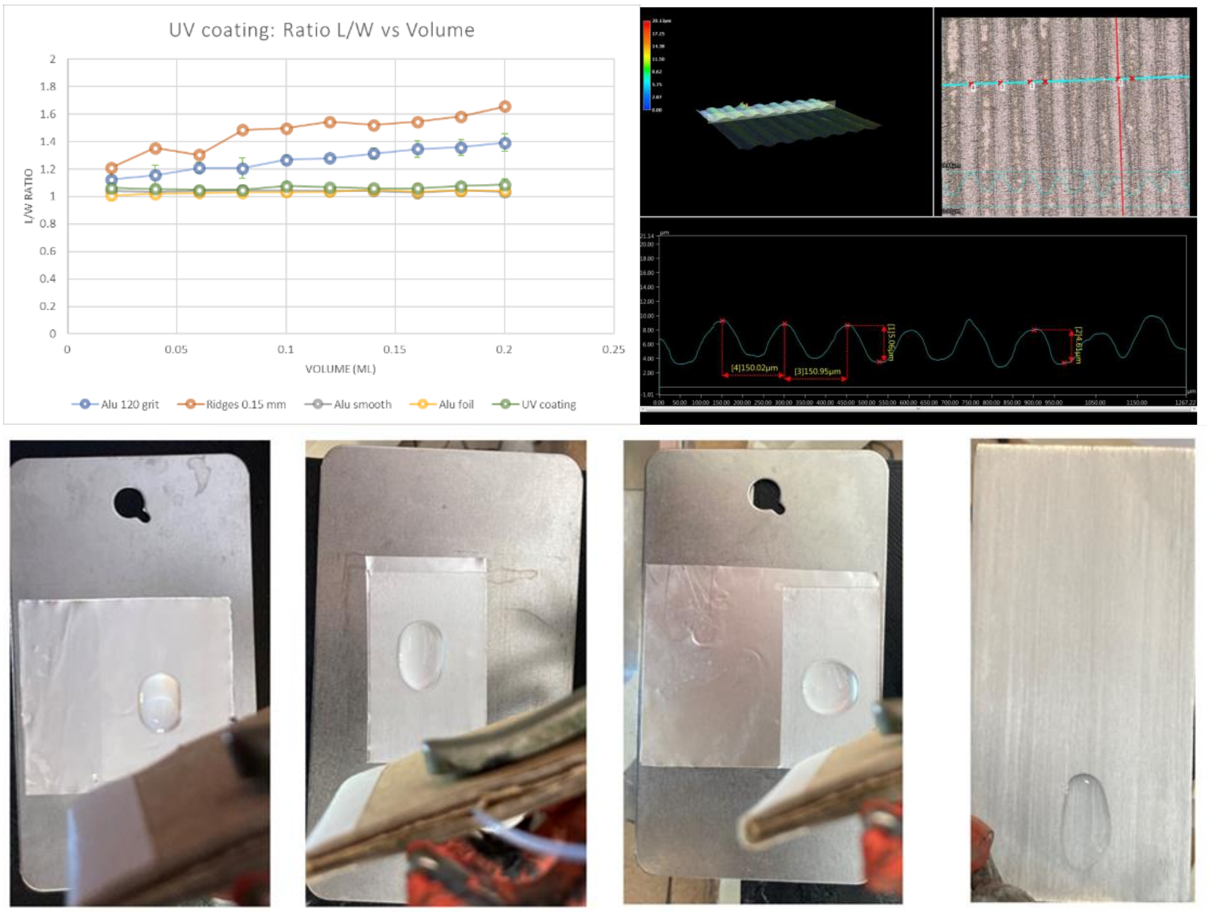


Figure 5: (left) picture of wetting behavior on sanded surface (middle) relation between aspect ratio for different sanded samples with different grid sizes (right) 3D images with four times height exaggeration of directionally sanded surfaces plus a blank sample : A) 60 grit, B) 120 grit, C) 600 grit and the blank sample D) 3000 grit randomly sanded. All rectangles are of size 945 x 1260 µm. The color code is different for each sample. Dark blue always has height zero. For bright red, the height is: A) 31, B) 28, C) 13 and D) 25

This is expected to come from the fact that the surface roughness is more defined which is based on the 3D microscopy images.

The directional surface roughness can also be produced using an electrostatic printing technique. At Qlayers this technique was developed for other purposes. However, as the technique could be beneficial in the application of the transition, we performed basic research on how these structures can help in producing a desirable LEP transition. The results from Figure 6 showed that the printed microstructures indeed promoted directional surface wetting.



Pitch 0.2 mm Pitch 0.15 mm Pitch 0.13 mm Alu 120 grit

Figure 6: (top left) Results from directional wetting tests (top right) microscopy image from printed ridges (bottom) The result of different surface roughness on the wetting (bottom left 3 pictures are printed microstructures with a spacing between 0.13-0.2mm and (bottom right) is a unidirectional sanded piece of aluminum.

Corona treatment

By use of a corona discharge apparatus, ions can be blown over the surface. This is a soft method of ionization of the air molecules. It makes it possible to improve the bounding of the coating to the surface. This was achieved by the increase OH and COOH groups on the surface. The use of corona treatment was tested; however, the effect was not significant enough to be useful for the AIRTuB project.

Plasma treatment

There are multiple kinds of plasma treatment, atmospheric plasma treatment, flame plasma treatment, and chemical plasma treatment. In the scope of this research, we only focused on atmospheric plasma treatment since it is the most useful and safe method to apply on wind turbine blades. Atmospheric plasma produces free radicals that when hitting the surface can create polar groups on the surface of the material. The polar groups will form stronger bonds with the coatings applied on top, meaning mechanical performance can be improved. Next to that, it increases the surface free energy of the material which leads to better wetting of the material.

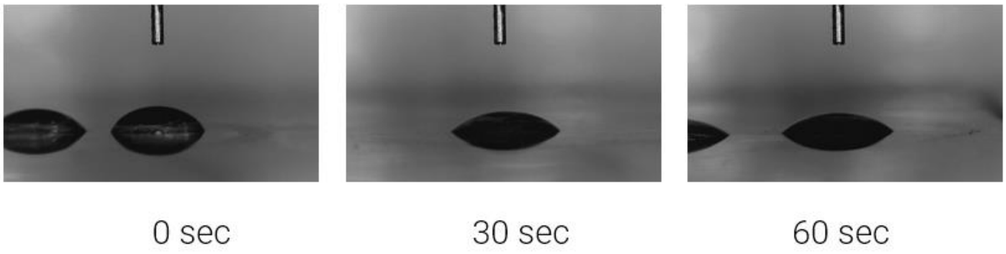


Figure 7: Plasma treated sample demonstrating the improved wettability with different duration of plasma exposure (test with water on plasma-treated aluminum).

By masking an area before the plasma treatment, the wetting can be affected locally. This makes it possible to tune how a polymer or water is wetting the surface. The picture below shows a test that was done with a diamond shape and a square.

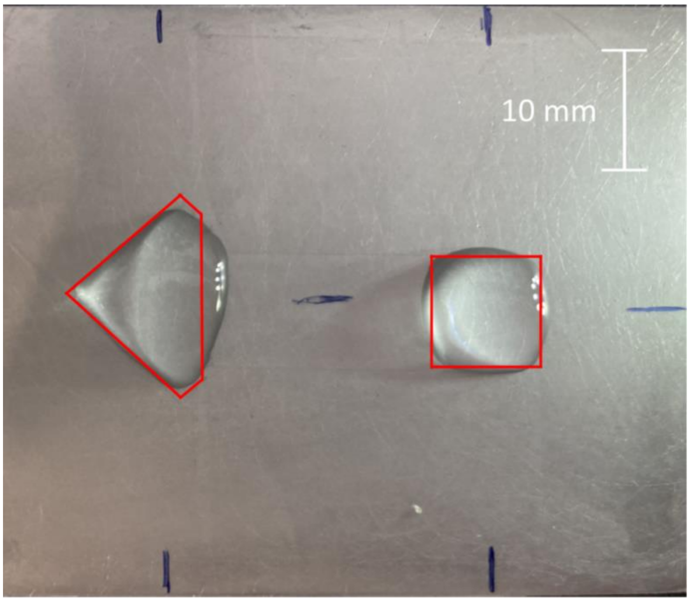


Figure 8: Plasma treatment on an aluminum substrate with the edges of the shape being masked between plasma treatment and the mask being removed after treatment.

Combined surface treatment

When a combination of surface treatments is made the direction wetting effect can be improved. The best possible pre-treatment to produce the transition was expected to be a combination of a microstructured surface and a plasma treatment. The idea is that the surface in the ideal scenario is wetting in only one direction, this allows for some tolerance in the application itself. If too much material was deposited in the transition, it will not exceed the determined borders set by the microstructure. It would force the polymer to flow out in the direction parallel to the LEP tape. The idea of combining a riblet microstructure with a plasma-treated surface was confirmed with experiments. The result of this experiment is shown below.

Figure 9: Plasma treated riblets which show a clear direction wetting with distinct borders.

In conclusion the best method for an easy application is by first applying a microstructure and finishing with a plasma treatment. Next the application, in this case a printing process of the transition was researched.

Research on printing process

The LEP sticker is the most convenient method for the application of a LEP in the factory and in the field. However, this comes with the downside of the step in thickness which disturbs the laminar airflow with the consequence of reducing the efficiency. That is why we as Qlayers looked at a method for the application of a smooth transition to maintain an undisturbed airflow. As Qlayers, we have developed a printing method for applying riblet structures. It could aid in the transition's production as a pre-treatment as shown in the previous chapter. However, the riblet printing technology was not fully fitting the application of the transition. Therefore, we started with a brainstorm on how the transition could be produced. This session resulted in a few possible concepts being built and tested. One of these methods showed promising results and gave use proof-of-concept. Based on this concept we continued our development. Since the technology developed for the application can be patented, specific working principles are not described here. We will only discuss the most important results.

The first step in understanding the application method was to move the prototype printhead manually over a surface (as shown in Figure 10). This showed that the technology has the potential to apply a transition that can meet the set requirements. However, it also showed the clear need for a more controlled flow rate and motion of the head to provide a consistent transition.

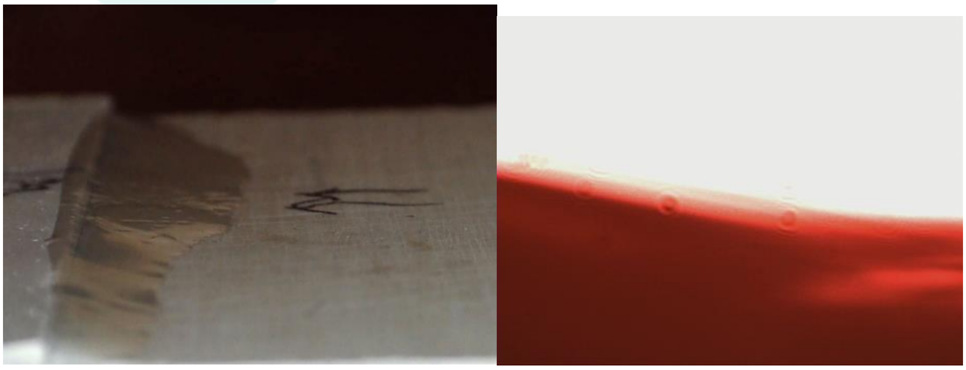


Figure 10: (left) Manual applied transition (right) Microscopy of manual applied transition.

Curing is essential to guarantee a consistent transition and potentially the need for building up the transition in multiple layers. To examine how curing time is affected by varying intensities, investigations were carried out. Figure 11 illustrates an instance of such a study. The results indicate that for the chosen coating, the curing time can be reduced to under 2 seconds, which is a feasible curing intensity for the intended application. However, there is still potential for further improvements.

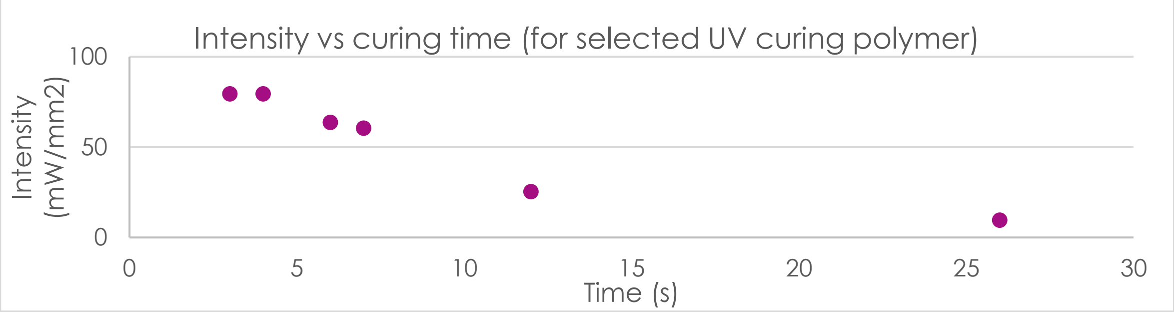


Figure 11: Intensity vs. curing time.

Based on the learnings of the experiments a new head was designed that could be implemented on multiple actuation systems and which could produce a consistent result by designing multiple subsystems for the control of the different parameters: A polymer extrusion system for the application of a uniform layer, a curing system, and a suspension system. More details on the development of the printhead are reported in the chapter methodology.

Research on automation

The research on the transition from manual to automated printing in lab conditions was done using a CNC platform. To ensure the effectiveness and efficiency of the printing process, it's essential to automate the printing process. However, for small-scale testing purposes, a robotic arm would be excessive and unnecessary. Therefore, we decided to purchase a small CNC machine instead as shown in

Figure 12, which is more suitable for testing the printing method at a smaller scale. The CNC machine will allow us to test the printing process while ensuring that the quality of the printed output meets our requirements. By doing so, we can make any necessary adjustments to the printing method before scaling it up to larger production runs.

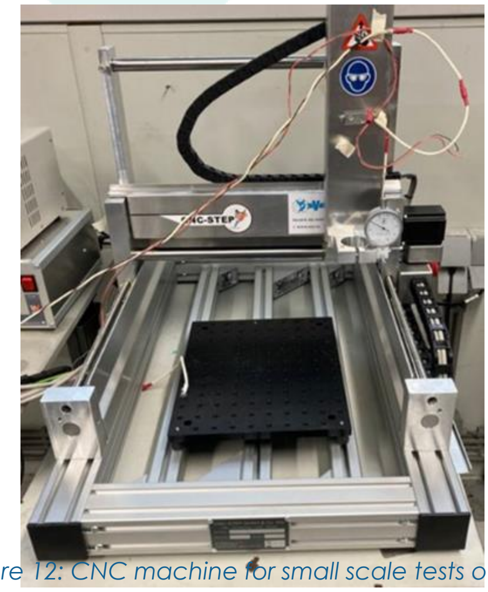


Figure 12: CNC machine for small scale tests of the application head.

This machine gave us the capabilities to produce the transition in a much more controlled way leading to samples as shown in Figure 13.

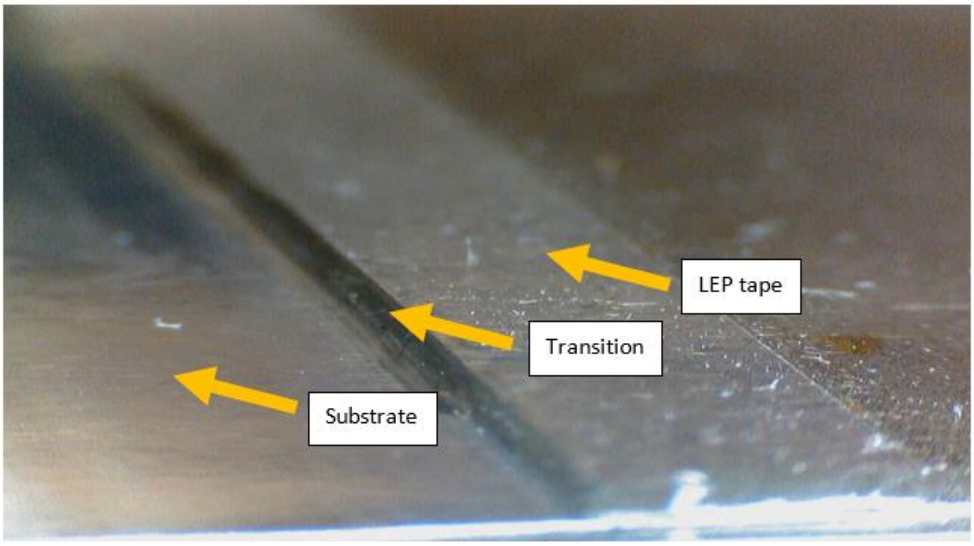


Figure 13: Automatic applied transition.

Eventually the LEP transition application head needed to be integrated on a robotic arm (ABB IRB-4600) to deal with the curvatures of the leading edge of the blade since the CNC does not have as many degrees of freedom to rotate. Testing with a robotic arm is not an optimal solution since setting up the robot requires a lot of time. However, since it is necessary for the application on the wind tunnel section the research and development already started on how to control the arm. The robot needs to know its distance from the blade to avoid a collision. Also, it's important to check if the robot can reach the full wind tunnel section for the application of the LEP transition. For that reason, simulations were performed in a program called robot-studio. These simulations were successful. The next step is to do real-life tests on a section to see the robot's performance. The step after that is to do a full integration and performance test on a dummy section and finally apply the coating on the wind tunnel model for the aerodynamic testing.

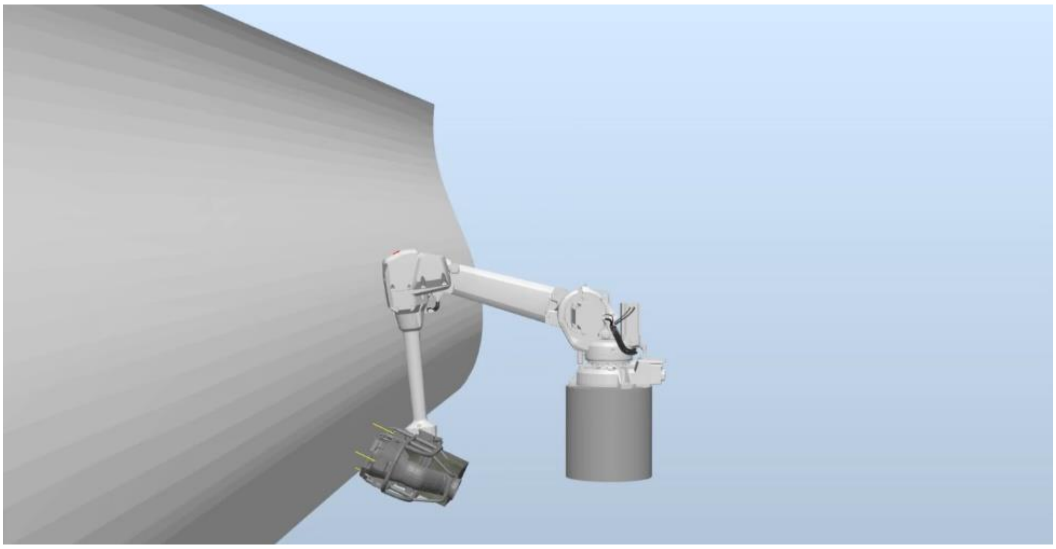
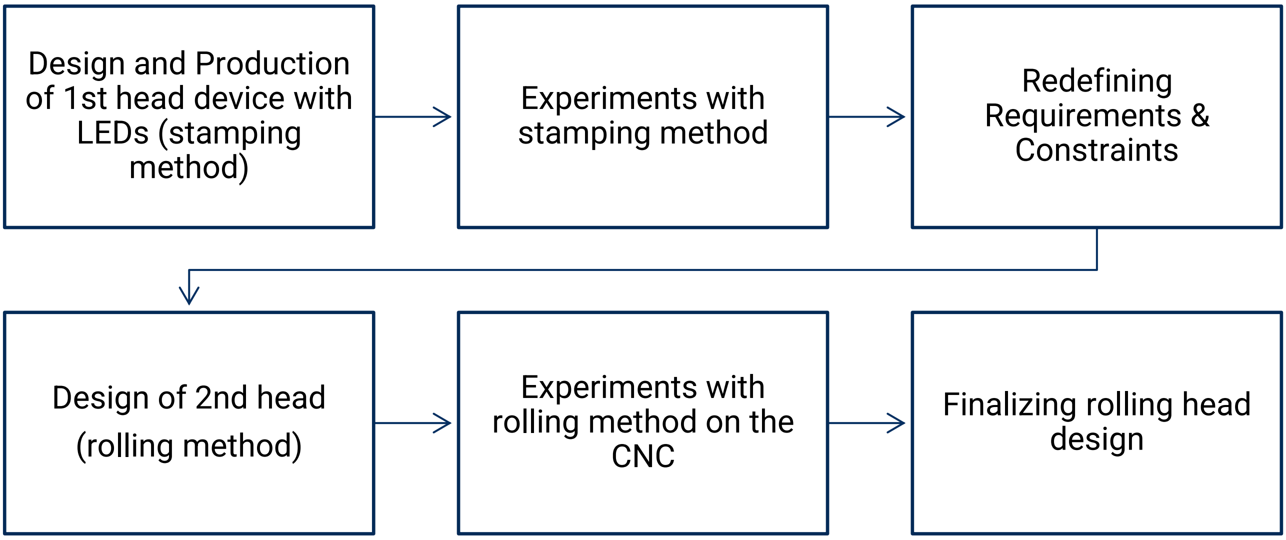


Figure 14: Screenshot of Robot studio.

Methodology

Production of Printing Head

Methodology evolution of producing the printing head:



UV Curing

The polymer coating used to make the transition coating requires UV radiation to trigger cross-linking to become a hard solid material, called the curing process. The requirements to obtain a high-quality finish for the AIRTuB project were:

- Exposure to UV must provide solidification without deformation.
- Provide necessary curing speed to fulfil automation requirements.
- Compact and light in-order to be mounted on a robot.
- Shielded the light from the surrounding environment for safety.

To provide the necessary illumination, experiments and test setups were built to study these requirements. These experiments focused on understanding parameters such as the intensity incident on the surface, light distribution, exposure time and deformation effects. Using these parameters, an optimal UV setup was constructed that had the necessary radiation beam, distance to the substrate to provide the necessary intensity and necessary surface exposure.

The UV requirements and constraints were considered for the head's design.

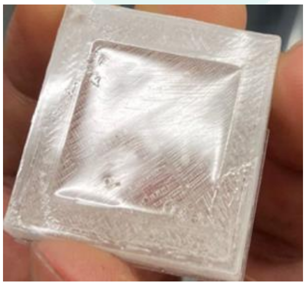


Figure 15: Example of curing sample for testing curing parameters.

Requirements & Constraints

The requirements and constraints of the head were redefined after the experimental results of the stamping method using the curing setup.

1. We determined the workable dimensions for the head which can apply a desired transition.
2. We determined the minimal process speed to be 1.5mm/s.

Rolling Method (distance and pressure control)

The next component in the design involves a rolling head mechanism that can print the transition on the LEP. In this setup, a rolling head that simultaneously moves parallel to the LEP, deposits the polymer, and cures it with UV was designed. The advantage of using a head with a roller is that the head is in direct contact with the surface making sure that the deposition can happen at a fixed distance from the surface and that deviations of the head actuator does not influence the distance to the surface.

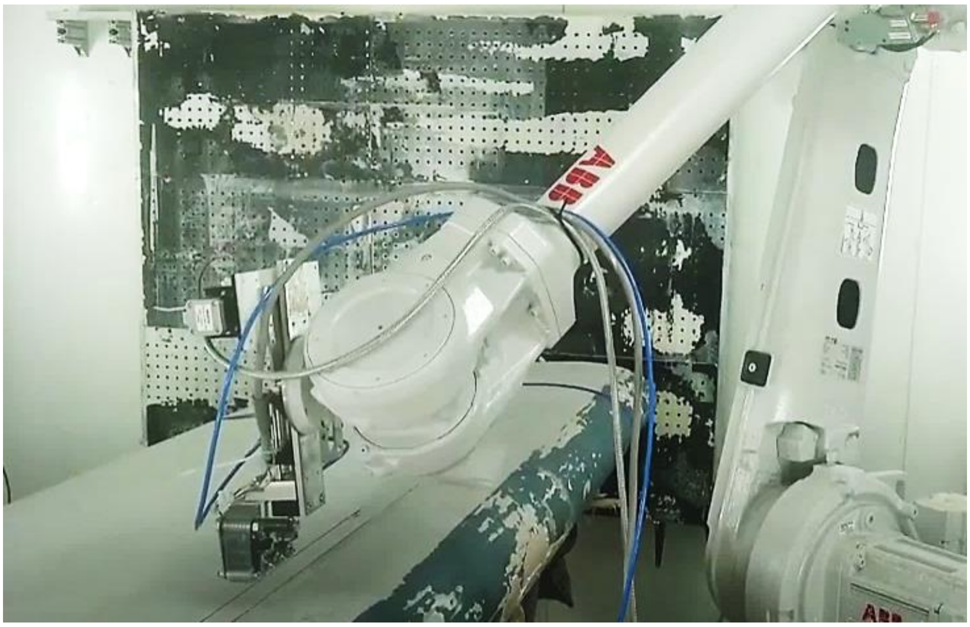


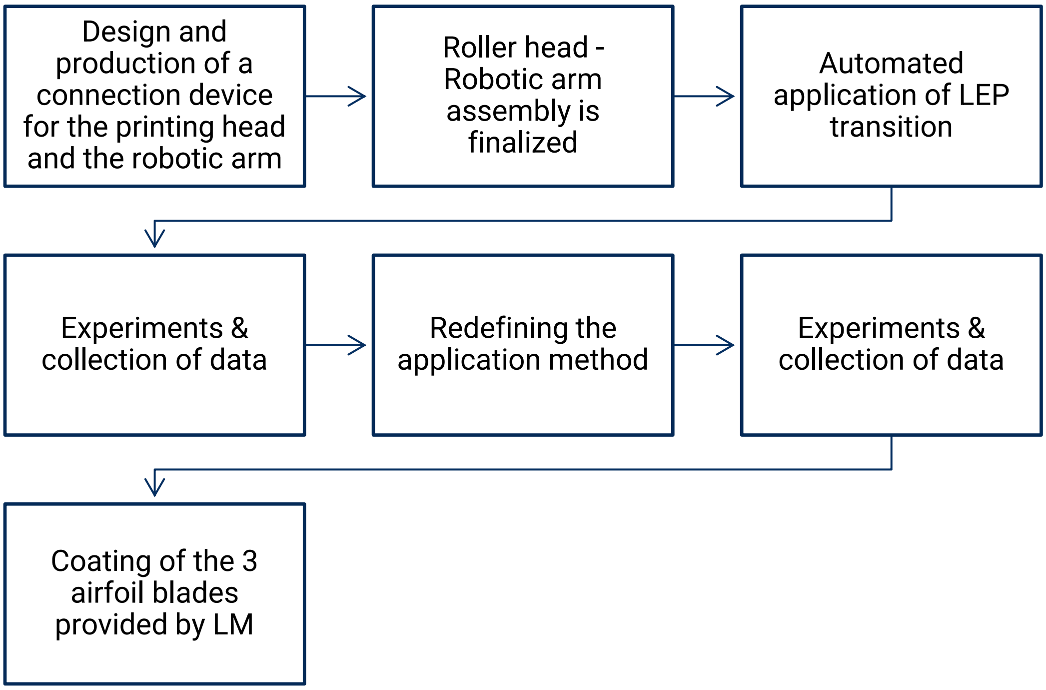
Figure 16: Automated application of LEP on wind blade using the roller method.

The UV resin that was used to manufacture the transition was selected after repeated experimentation for optimal adhesion and durability. The resin bonded optimally with the LEP material provided by LM wind power. However, the LEP material delivered with the blades for the final application was different than our researched material, which did not adhere optimally with the resin that we researched with. Hence, we had to choose a different resin in our final application.

Experiments with the roller were first performed using a CNC machine. The CNC system was accurate and easy to use for development purposes. After conducting the development and testing plan in the CNC system, the printing method was implemented on a robotic arm. The challenge we faced, adapting the roller on the robotic arm was that we were operating at the limit of the machine specs, resulting in a loss of motion linearity, which in turn produced ripples on the coating. We concluded that the variations in the z-axis caused pressure differences interfering with the motion of the roller.

Therefore, Qlayers developed an add-on system to compensate for z-axis variations and maintain the pressure constant and. The prototype add-on system improved the quality and success ratio of our coating system. Further development is necessary to hit a 100% reproducibility ratio.

Printing head on Robotic Arm



When a reproducibility of 80% was achieved with the roller method on the CNC, the system was ready to move to the step.
A simulation was run using the robot’s software to check that the repeatability and size of the robot was suitable for our application.
Once this was confirmed, we assembled the printing head to the robot mount.
The tests showed us that the repeatability and resolution of the robot was not good enough for the project. We had to add a pneumatic leveling system to counter act on this which resulted in a decrease of 50% in the reproducibility of our results.

Final Application method

The final application method was done by applying the transition in three steps:

1. Surface preparation by cleaning the surface.
2. Deposition of the coating.
3. Curing of the coating.
4. As we had issues with the robot, we did some manual adjustments to avoid the ripples.

A syringe extruder was filled with the UV curable resin and the liquid was homogenously applied (constant speed and flow rate) at the edge of the LEP. Next the robot arm would do another pass for curing using a 405nm LED array that was then passed at constant speed (therefore illumination dose was constant) over the length of the airfoil.

Figure 17: Finished wind tunnel model (left & right) and close-up indication where the LEP is applied (right).

Results

After coating the three wind blades with the LEP, Qlayers sent them to LM Windpower for wind-tunnel testing. LM's objective for the AIRTuB project is to develop a 3D printed chamfer to minimize the aerodynamic impact of the addition of the LEP. For every airfoil model, the data is presented for lift, drag and glide ratio (lift over drag) for different Reynolds numbers. In the following graphs, the colors illustrate the following:

- Blue – clean configuration
- Green – clean with application of LEP
- Red – clean with application of LEP and 3D printed chamfer

The results for all 3 models show that models shows that the loss of applying LEP is partially regained by adding the chamfer. There were also some areas with a small defect which can be observed in the wind-tunnel results.

The lift, drag and glide ratio for the 3 different tested Reynold numbers are presented in the following figures:

DU08-W-210

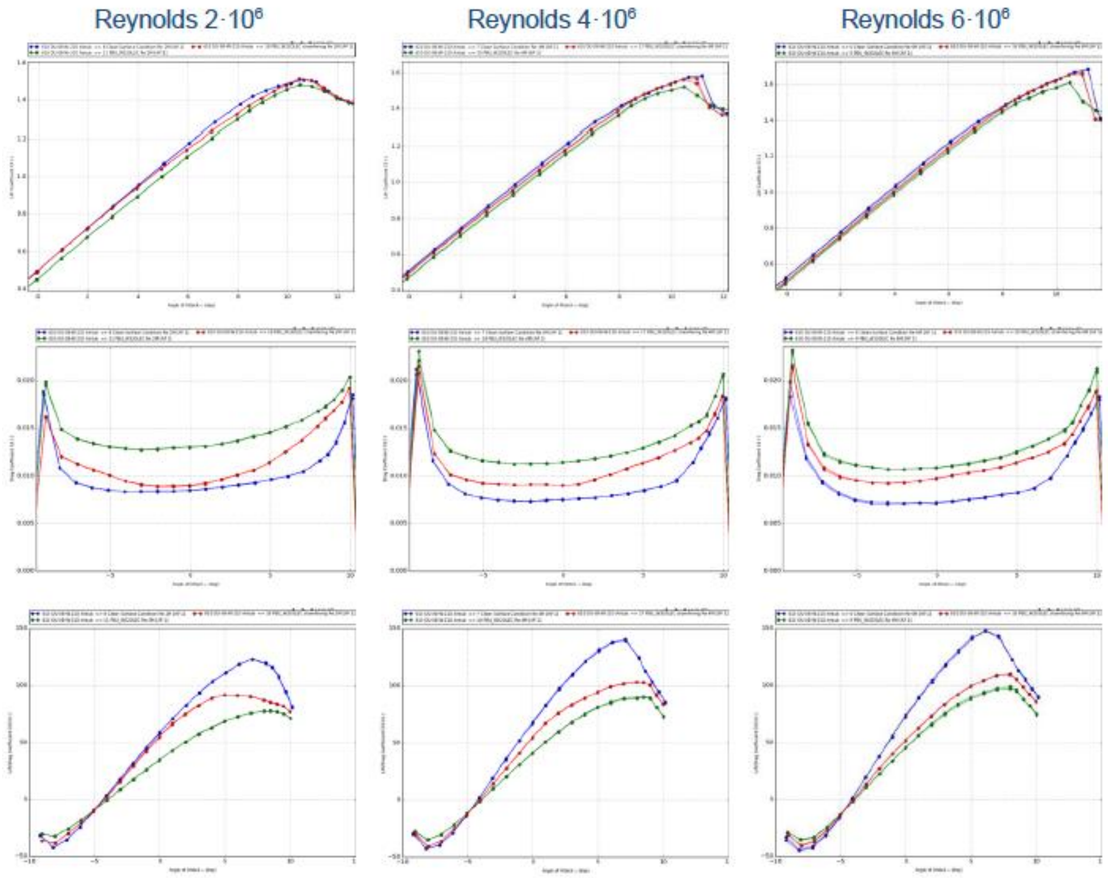


Figure 18: Results for DU08-W-210.

NACA63-621

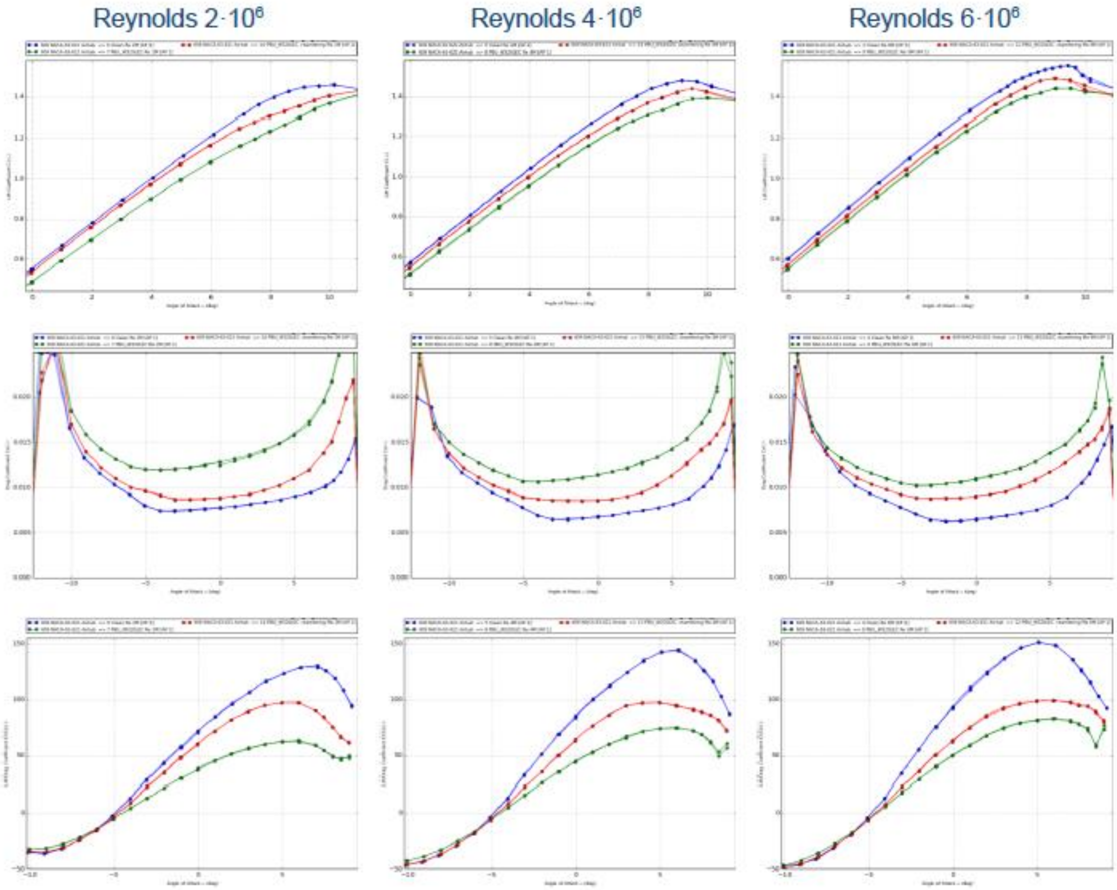
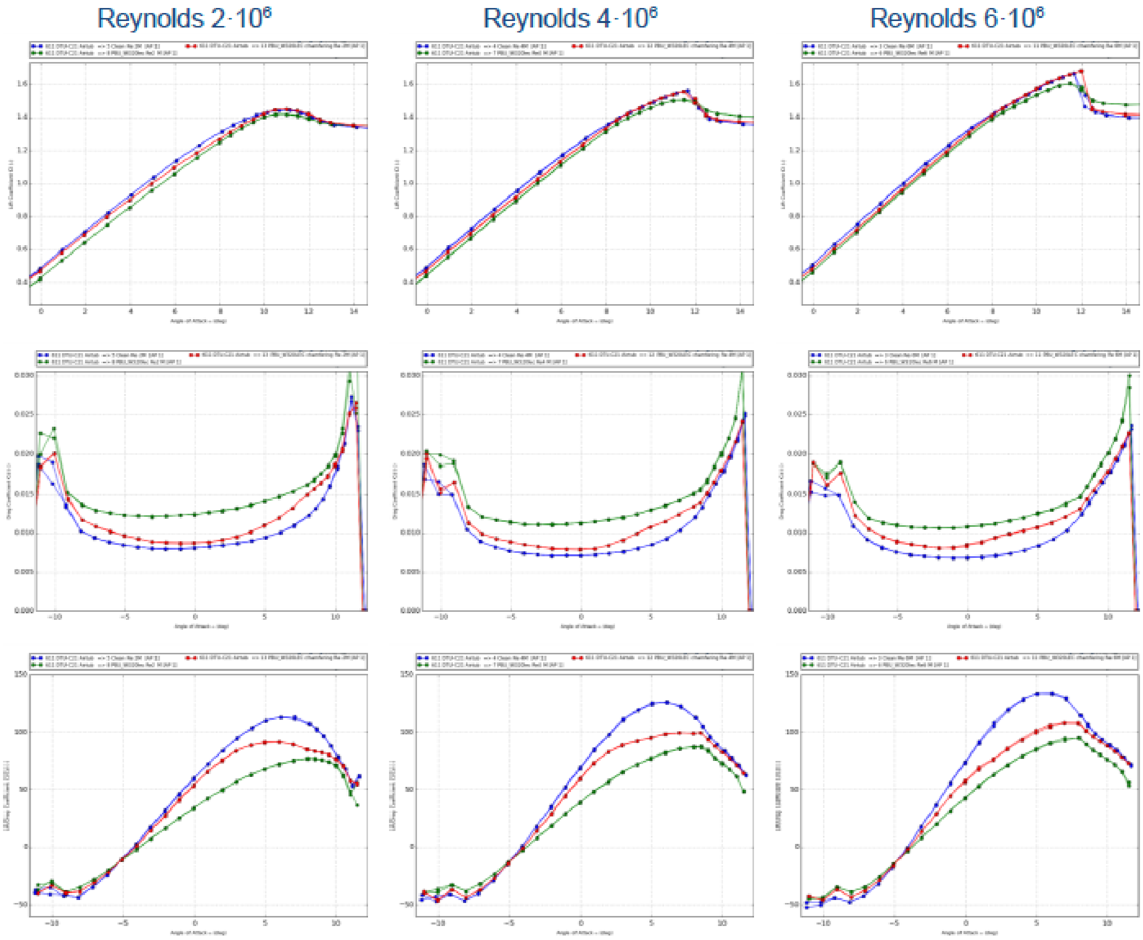


Figure 19: Results for NACA63-621.

DTU-C21



Reynolds $2 \cdot 10^6$ Reynolds $4 \cdot 10^6$ Reynolds $6 \cdot 10^6$

Figure 20: Results for DTU-C21.

More information regarding the testing in the wind tunnel testing can be found in the LM Report.

Figure 21: Chamfering on DTU-C21 suction side (down-wind).

It can be observed that for all three models the loss of applying PBU is partially regained by adding the chamfer. However, adding chamfering restores the lift for the maximum lift of the NACA model.

The Levelized Cost of Energy (LCoE) is calculated as the total energy cost over the lifetime of a system divided by the electricity produced over its lifetime. This can be expressed by the formula:

$$LCoE = \frac{Total\ Energy\ Cost\ over\ Lifetime}{Electricity\ Produced\ over\ Lifetime}$$

After conducting wind tunnel measurements, it has been observed that the application of a post-applied Leading-Edge Protection (LEP) can result in a reduction of 0.42% in the LCoE of a typical modern offshore wind turbine. It is worth noting that the maximum possible reduction in LCoE, based on theoretical calculations, would be 1.16%.

Conclusion

Qlayers has focused on the application of the LEP transitions as part of WP5. The production of the smooth transition has been attempted using trialing many methods such as sanding, manual filling, and automated roller application. Overall, the transition coating was applied achieving promising results, as it can be seen in the LM Report. Nevertheless, to achieve higher accuracy, speed, and reproducibility more research needs to be conducted regarding the automated motion control of the system. It can be concluded that the curing head with a roller system and integrated curing LEDs (405nm) in combination with a coating deposition system made it possible to apply a desired aerodynamic transition in one motion with a speed of 70mm/min. Even though during the application on the final wind tunnel sections some manual adjustments had to be made we are confident it can be done on a full-scale wind turbine blade.

After coating the 3 wind tunnel sections from LM, the results showed that the loss of aerodynamic performance caused by the LEP is partially regained by adding the chamfer. Based on the wind tunnel measurements for a typical modern offshore wind turbine, there is a reduction of 0.42% in Levelized Cost of Energy (LCoE) caused by the post-applied LEP towards additional chamfering. The theoretical maximum achievable LCoE is 1.16%.

It can be concluded that the transition application method improves aerodynamic performance but can still be improved in terms of automation process with the robot is not precise that being the reason for reproducibility issues, causing ripples on the transition coating. Also, the UV cured polymer used in this project was not an optimal match with the LEP material. Further studies and experiments must be conducted to improve the performance of the blade with the LEP tape and transition application method.

Recommendations

To scale-up the LEP transition coating process, improve its accuracy and repeatability the following steps are recommended:

A. Integrating a more precise pneumatic suspension system to suppress motion inconsistencies related to the robot precision- z axis wobbling- and surface roughness.

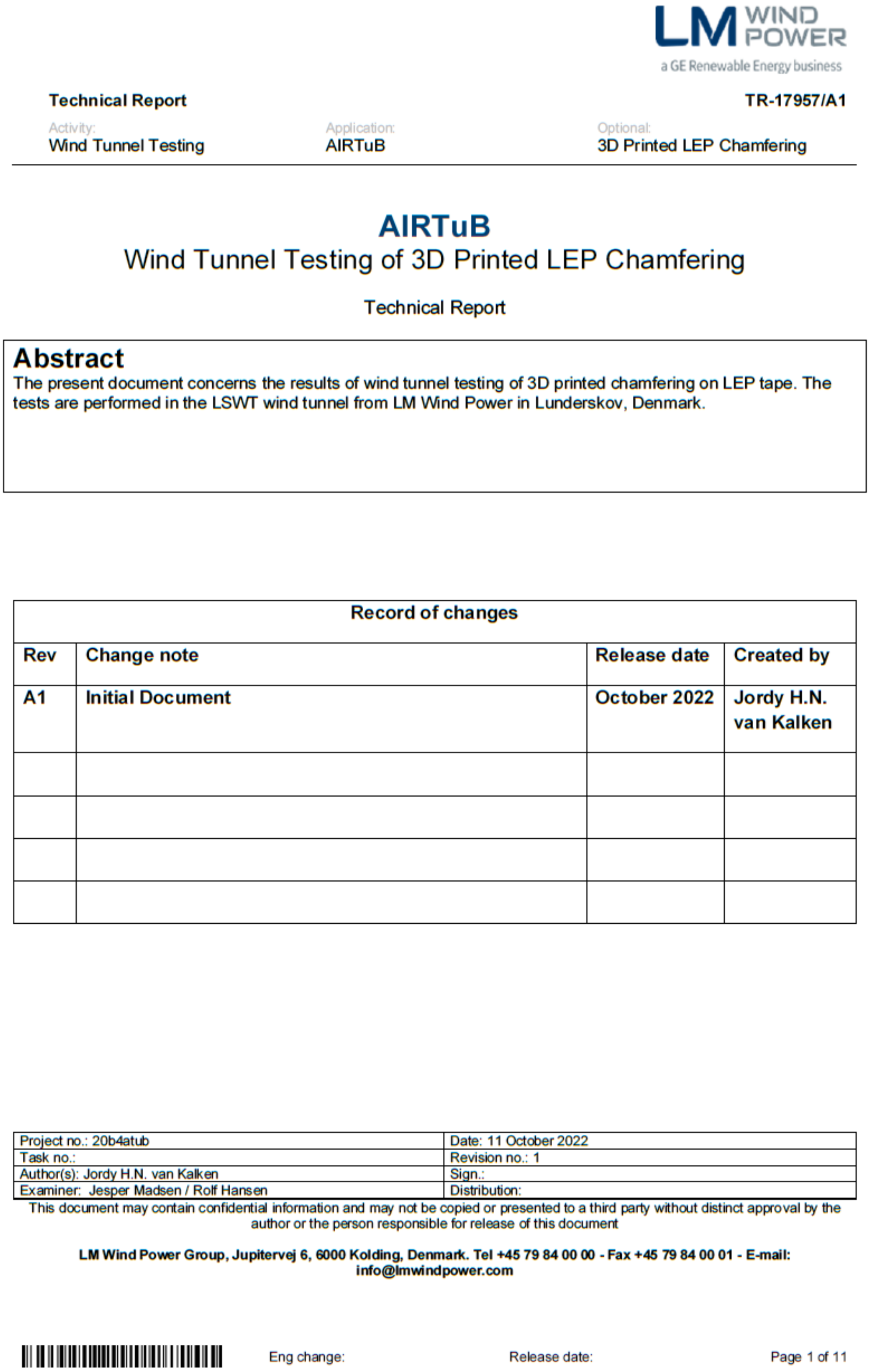
B. Automate the alignment of the head with respect to the LEP. This is a hard requirement for application on a real blade due to its total length and slight changes in the path of the LEP.

C. For life-sized wind blades, the system should be able to move along the blade's span. This can be done with a robotic arm on rails or a revised concept.

D. For offshore maintenance, a crawler system could be developed that will move along the span of the wind-blade. The same system could be used indoors.

Appendix

LM Report



LM WIND POWER
a GE Renewable Energy business

Technical Report **TR-17957/A1**

Activity:	Application:	Optional:
Wind Tunnel Testing	AIRTuB	3D Printed LEP Chamfering

AIRTuB

Wind Tunnel Testing of 3D Printed LEP Chamfering

Technical Report

Abstract

The present document concerns the results of wind tunnel testing of 3D printed chamfering on LEP tape. The tests are performed in the LSWT wind tunnel from LM Wind Power in Lunderskov, Denmark.

Record of changes

Rev	Change note	Release date	Created by
A1	Initial Document	October 2022	Jordy H.N. van Kalken

Project no.: 20b4atub	Date: 11 October 2022
Task no.:	Revision no.: 1
Author(s): Jordy H.N. van Kalken	Sign.:
Examiner: Jesper Madsen / Rolf Hansen	Distribution:

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Eng change: Release date: Page 1 of 11

Contents

1 Introduction

In the AIRTuB project WP5, the objective is to develop a 3D printed chamfer to minimize the aerodynamic impact of a manually placed Leading Edge Protection (LEP). For this, qLayers (the partner in the work package) has developed a 3D printing technique that is capable of 3D printing such chamfer directly on the blade surface.

This work package is intended to apply such chamfer on 3 wind tunnel models and have those tested in the LM Wind Power owned wind tunnel (LSWT – Low Speed Wind Tunnel).

This assessment is extended to include a very basic and simplified assessment of the alteration in levelized cost of energy, to get a feel for the worth of such technology.

2 Testing Equipment and Set-Up

2.1 *Low Speed Wind Tunnel - LSWT*

In Figure 2-1 the LSWT is shown as an overview with the main components indicated in which can be seen that the LSWT is a wind tunnel of the closed-circuit type. The tunnel has a maximum test section flow speed of 105 m/s.

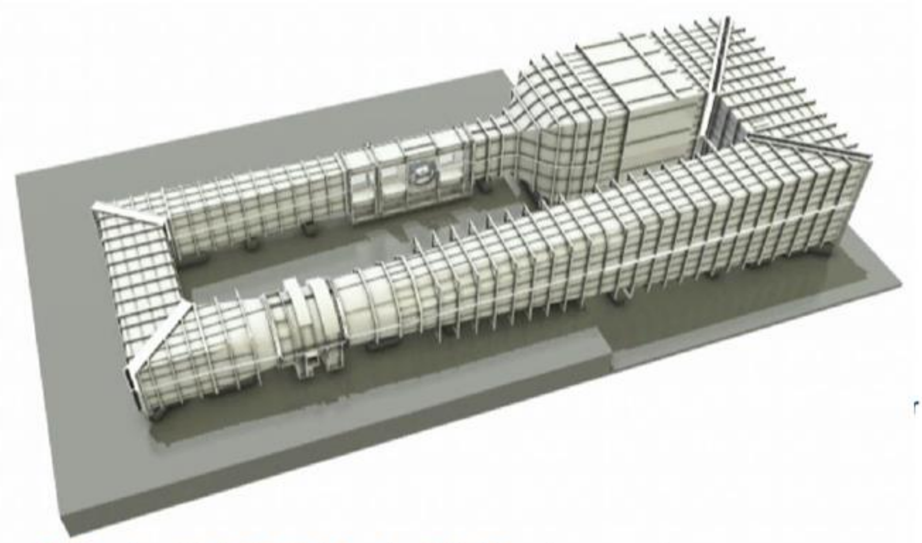


Figure 2-1: Overview of the LSWT Wind Tunnel with its different components

Generally, the tests performed in the LSWT are 2D profiles spanning the wind tunnel width (1.35 meters) connected to two turn tables such that multiple angles can be measured in a single run. Most tested profiles have a chord of 900 mm. As there is a limited option for density and/or temperature change, a maximum Reynolds number of 6 million can be obtained for these profiles.

2.2 *Airfoil Models*

To minimize the risk of a failed experiment, it was chosen to perform tests on 3 models. Then, in case the chamfer or LEP gets damaged during transport, there are 2 additional opportunities.
The models used for this test are (in order of chamfering application time):

- DU08-W-210
- NACA63-621 and
- DTU-C21

The normalized geometries for these airfoils are presented in Figure 2-2.

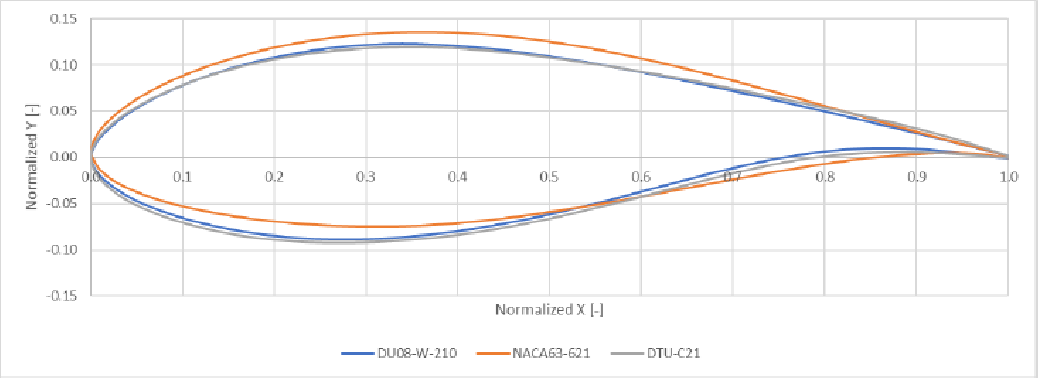


Figure 2-2: Normalized Geometry of Airfoil Models used in the project

The models are aluminum 2D geometries with a span of 1.35m (panning the complete wind tunnel test section) and a chord of 900mm.

The applied leading edge protection (LEP) is a tape solution (ProBlade Ultra - PBU) which has a thickness of 880 µm including adhesive. It has been chosen to use a small width (320 mm) and symmetric around leading edge application to maximize the impact on performance. This would allow for a larger potential to regain by applying the chamfer. This means that the application is not similar to the commercially applied PBU.

The application of PBU is therefore:

- DU08-W-210: 14% chord on suction side (down-wind);16% chord on pressure side (up-wind)
- NACA63-621: 14% chord on suction side (down-wind); 16% chord on pressure side (up-wind)
- DTU-C21: 14% chord on suction side (down-wind); 16% chord on pressure side (up-wind)

For all 3 models the chamfer was applied on the suction side (down-wind) first whereafter it was applied on the pressure side (up-wind).

2.3 *Campaign Set-Up*

The models have been tested in 3 configurations:

- Clean (used as reference)
- Clean with Leading Edge Protection (ProBlade Ultra – PBU)
- Clean with LEP and 3D printed chamfer on both pressure and suctions side

These configurations are tested in for 3 different Reynold Numbers ($2 \cdot 10^6$, $4 \cdot 10^6$ and $6 \cdot 10^6$) for all 3 models.

2.4 *Logistics*

As there has been complications on transporting and setting up the 3D printing machinery from qLayers in Delft, the Netherlands to the Wind Tunnel in Lunderskov, Denmark, it has been chosen to have the models transported to the Netherlands for the application process. This means that the measurement process has been divided into 2 steps.

The process is described in below summation:

1. Preparing Wind tunnel models
2. Measuring models in clean surface conditions (no application of add-ons)
3. Comparing results with previous wind tunnel tests for consistency
4. Application of Leading Edge Protection (ProBlade Ultra – PBU)
5. Testing the models with PBU
6. Transportation of models to qLayers
7. Application of 3D printed Chamfering
8. Transport of models to LM Wind Power - Wind Tunnel
9. Testing of chamfered models
10. Processing and validation of results.

2.5 *Returned Models*

The models have been manually inspected after return for damages and application quality. Some notes have been made to consider during result processing:

- DU08-W-210 pressure side chamfer is quite sticky. The overall quality of the chamfer is worst on this profile. On the right side the chamfer is introducing a bump, which can be seen in the spanwise drag. Width of chamfer is around 30mm
- NACA63-621 has the nicest chamfer. Width is around 30-35mm
- DTU-C21 has the shortest chamfer – around 25mm

Even though there is the possibility in the processing to remove areas with poor application, it has been chosen to keep the results as average of the complete profile to highlight the status of improvement on average. The main reason for this is that an application in real life would be on a far longer distance and curved surface which makes it less conservative utilizing the results.

To illustrate this an example of the spanwise drag measured by the wake rake is depicted in Figure 2-3. Here it can be observed that the post-chamfered configuration has a better performance on the left side of the model than on the right side. Note that the red curve indicates the post chamfered configuration where-as the blue curve is the clean model and the green curve the pre-chamfered configuration.

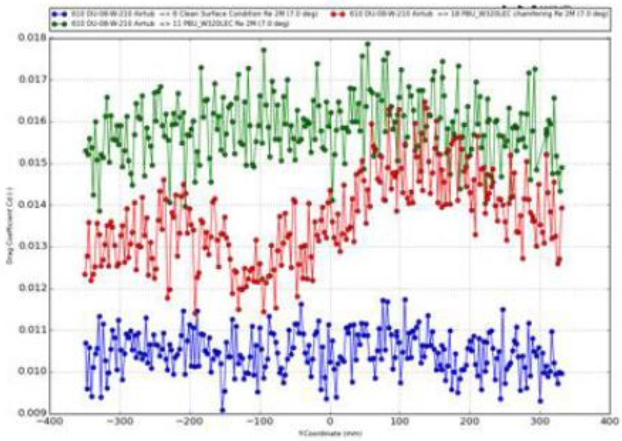


Figure 2-3: Example of Spanwise Wake Rake Drag results

Improvement on the application method could bring improvements to the result as well.

As example, the chamfering on DTU-C21 is presented in Figure 2-4.

Figure 2-4: Chamfering on DTU-C21 suction side (down-wind)

3 Results

The results for the tests performed are described in this chapter. For every model, the data is presented for lift, drag and glide number (lift over drag). Note that as pressure taps in the model have been blocked due to the LEP application, lift is based on wall pressure while drag is based on wake rake measurements.

In these plots, the colours are kept constant such that:

- Blue – clean configuration
- Green – clean with application of PBU
- Red – clean with application of PBU and 3D printed chamfer

The results show that for all 3 models, the loss of applying PBU is partially regained by adding the chamfer. Except for the NACA profile, the maximum lift is restored by adding the chamfering.

3.1 *DU08-W-210 - Results*

The lift, drag and glide ratio for the 3 different tested Reynold numbers are presented in Figure 3-1.

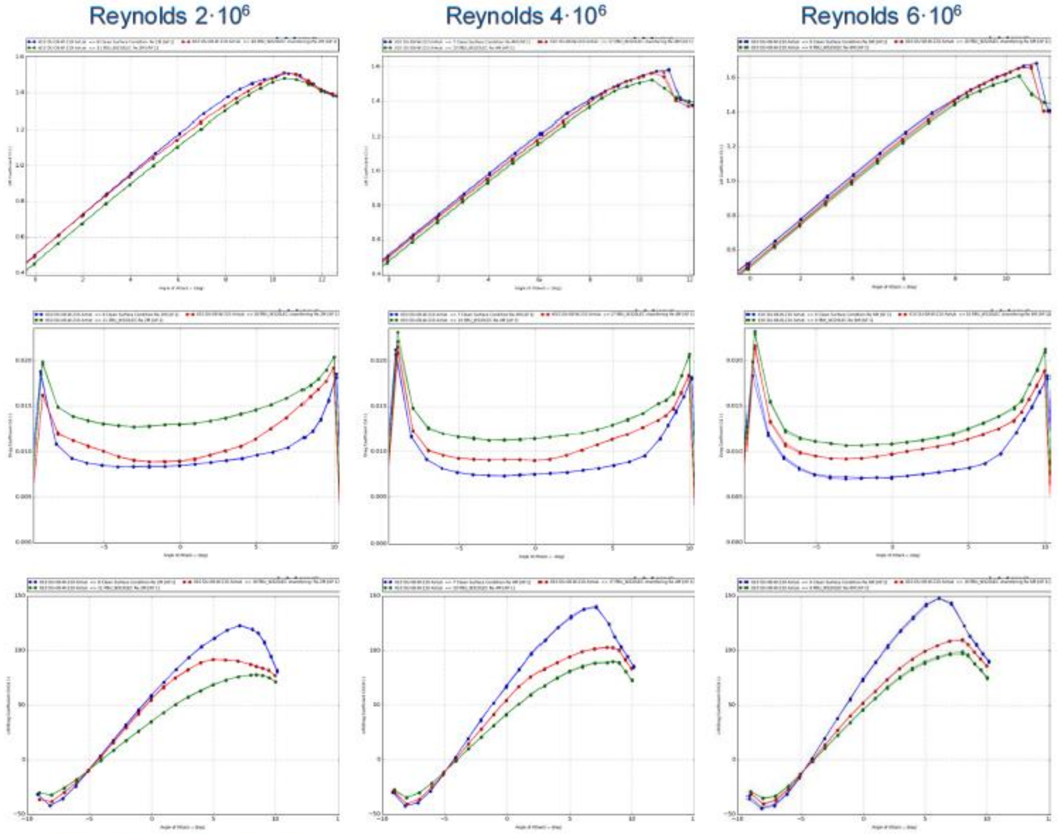
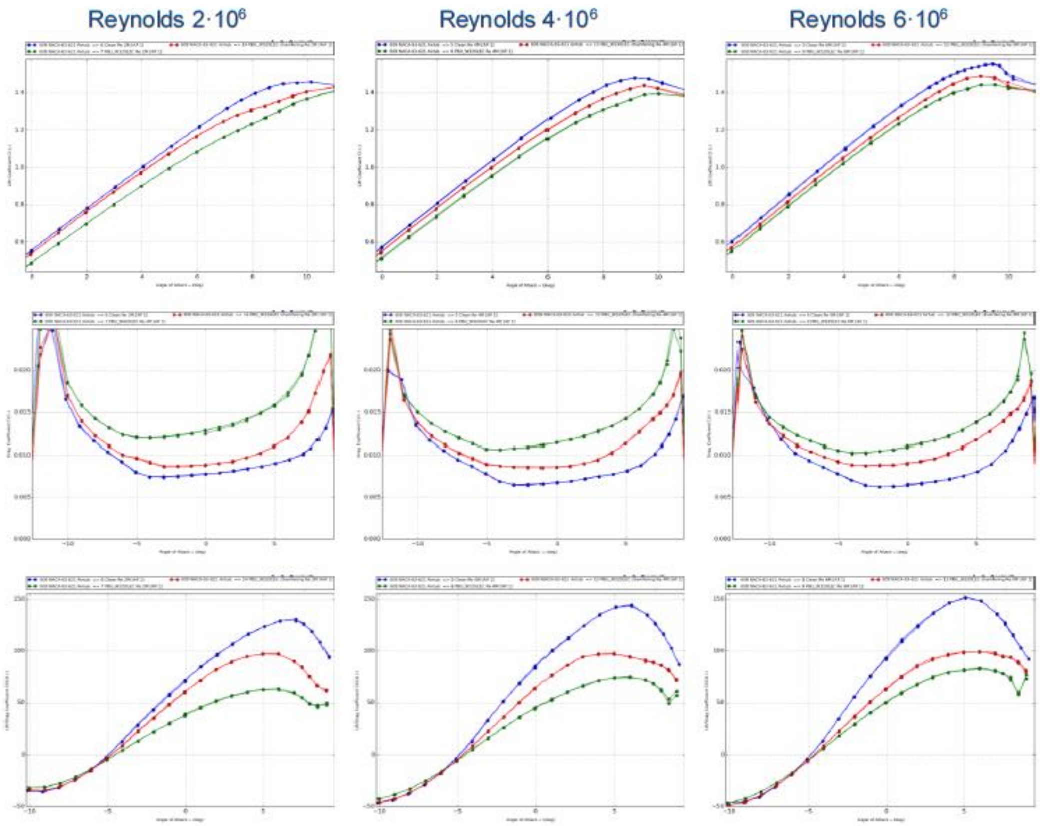


Figure 3-1: Results for DU08-W-210

3.2 *NACA63-621*

The lift, drag and glide ratio for the 3 different tested Reynold numbers are presented in Figure 3-2.

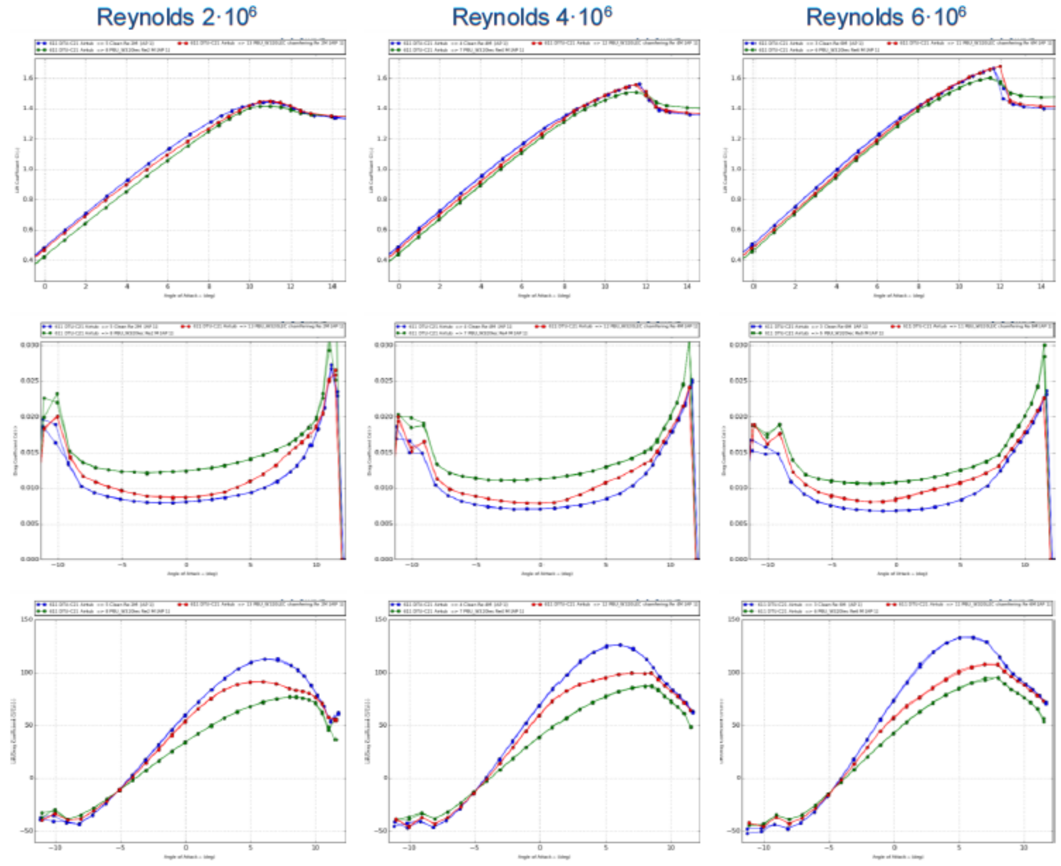


Reynolds $2\cdot10^6$ Reynolds $4\cdot10^6$ Reynolds $6\cdot10^6$

Figure 3-2: Results for NACA63-621

3.3 *DTU-C21*

The lift, drag and glide ratio for the 3 different tested Reynold numbers are presented in Figure 3-3.



Reynolds $2 \cdot 10^6$ Reynolds $4 \cdot 10^6$ Reynolds $6 \cdot 10^6$

Figure 3-3: Results for DTU-C21

4 Brief LCoE analysis

The Levelized Cost of Energy (LCoE) is defined as the ratio of total energy cost with energy production:

$$LCoE = \frac{Total\ Cost\ over\ Lifetime}{Electricity\ Produced\ over\ Lifetime}$$

The 2 main contributions to cost of energy are the blade cost and gain of the turbine. As such, the gain in Annual Energy Production (AEP) should be worth the increased cost of applying the chamfer.

Using the data from the wind tunnel a relative change in lift and drag is utilized to get an understanding of the impact on the LCoE of a regular offshore blade with post-applied LEP. The basis for this calculation is a modern offshore wind turbine blade with the outer 28% of blade span covered with a similar leading edge protection as used in the wind tunnel tests.

Note that the change in LCoE is depending on the altered cost of the application method. As the method is in low TRL, this cost change is hard to justify currently. In any case, the cost change will be minimal towards LCoE as the cost of applying the chamfer in this method is nearly insignificant in comparison to the total cost of wind turbine, manufacturing, logistics, maintenance, and operation during the lifetime of a windfarm. Any change of Annual Energy Production (AEP) is a direct influencer on the LCoE.

The calculation is severely simplified and is a pure reflection of applying the chamfer vs not applying the chamfer on the post application of LEP. It has also to be noted that several alternatives are available to 3D printed chamfer application which lead to similar results.

The results of the wind tunnel measurements show that the reduction in LCoE from a post-applied LEP towards an additional chamfering is in the order of 0.42% for a typical modern offshore wind turbine. The maximum achievable LCoE reduction would equal nullifying the LEP impact which would be 1.16%.

Project Details

Coordinator and participating companies in WP:

Qlayers: Ruben Geutjens

LM Wind Power: Jordy H.N. van Kalken

Execution of the project

1) The problems (technical and organizational) that occurred during the project and the way in which these problems were solved.

The problems faced throughout the project are explained in detail in Methodology and Conclusion

2) Explanation of changes to the project plan

No changes on the output

3) Explanation of the differences between the budget and the costs actually incurred

The following paragraphs explain the difference in hours and hardware costs incurred:

The initial idea of the AIRTuB project included higher hardware costs. The assumption was that we could work with off the shelf components. During the project we decided to do the development step by step. We did this with small proof-of-concepts to minimize risk. We were also able to accomplish this largely with the hardware that was already available within Qlayers.

After the initial testing, we observed that we could also do certain parts more simply and cheaper than initially expected. This was interesting from a commercial perspective as we could reduce the hardware cost but at the cost of extra hours. Furthermore, the choice of components allowed us to make the head simpler, again finding the exact components and materials came at the cost of time. An example of this is figuring out a suitable UV curable polymer which does not suffer from oxygen inhibition.

The application of the transition was done using a robotic arm, the hours of the robotic arm were not counted, due to the lack of hour registration on the internal hardware. The same goes for the other tools used for the project, this includes things like high voltage sources for pre-treatment, the material extruders, PLCs and microcontrollers, use of the spray booth, various UV lamps, etc.

3) Explanation of the way of spreading knowledge

Two AIRTuB Zephyros events including all the participants of the project:

1) Hosted AIRTuB WP5 Event (Smart maintenance for offshore windturbine blades by robotized coating technology) at Qlayers in May 2022
2) Event at NLR in November 2022 (presentation and poster presented to the participants regarding Qlayers results of AIRTuB project)

4) Explanation PR project and further PR possibilities

N/A