DEMOWIND 2
TEHE116121

Offshore Demonstration Blade (ODB)

Date	28 June 2019
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Number of pages	13
Project name	DEMOWIND 2
Project reference nr.	TEHE116121

Contents

1 Introduction

The large-scale deployment of offshore wind provides economically viable, secure, low carbon energy sources that meet the EU's climate change targets for 2030. The EU-wide target of 27% renewable contribution of final energy consumption in the EU as a whole by 2030 requires technological innovations capable of providing a significant breakthrough in lowering the Levelised Cost of Energy (LCOE).

In offshore wind, Operations and Maintenance (O&M) costs represent 16-23% of LCOE (sources: Tavner, Offshore Wind Turbine Reliability; & BVG Associates). Rotor O&M represents a large part of this cost, specifically issues around blade erosion and blade structural integrity. Furthermore, rotor aerodynamic performance is a key component to reduce LCOE, with an estimated 1% increase in Annual Energy Production (AEP) equating to 1% reduction in LCOE.

The Offshore Demonstration Blade (ODB) project aims to reduce the LCOE of offshore wind by up to 4.7% by demonstrating a set of blade technologies aimed at increasing the rotor energy performance and reducing O&M costs.

The ODB project will demonstrate the following novel technologies:

1. aerodynamic low drag add-ons;
2. leading edge insert for erosion protection;
3. structural stiffener to prevent damage due to shear distortion;
4. **fibre optic sensors to monitor shear distortion;**
5. **fibre optic sensors to detect Leading Edge Erosion and top coating performance;**
6. High-performance hybrid coating for leading edge protection;
7. Aerodynamic next-generation blade add-ons that are 100% retrofitable increase AEP (decreasing LCOE).

In this report **the work is described of the two fibre optic sensing technologies** that have been developed within the ODB project.

The project has been running from January 2017 up to and including March 2019, (end date 1st of April 2019). Although the project has been confronted with many delays, due to problems with the offshore wind turbine, TNO successfully developed two fibre optic technologies. One of them has been deployed in the offshore demonstration wind turbine in the United Kingdom (UK). The other technology has not been deployed in the wind turbine because representative tests in the laboratory made clear that the technology has a negative impact on the life-time of the Aerox LEP coating. When that became clear additional tests and modelling were done to valuate different trade-off to steer development in future.

This project has been realized with subsidy of the Ministry of Economic Affairs by means of the 'Nationale regelingen EZ subsidies, Topsector Energie', executed by the Rijksdienst voor Ondernemend Nederland (RVO).

The project has been coordinated by ORE Catapult (UK). More info about the project can be found on the ODB website: http://odb-project.com.

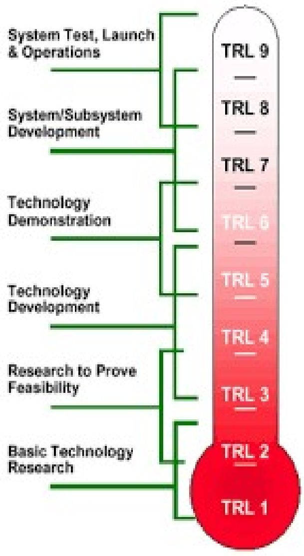
2 Progress of the project

2.1 Plan of work

The two technologies from TNO are sensor developments to monitor the structural enhancement of the blade (technology #4) and the leading edge erosion of the top coating of the blade (technology #5).

Since the ODB project aims to develop new technology reference is made to the Technology Readiness Levels defined by the European Commission, ranging from number 1, a first idea, to 9, successful commercial deployment shown in the picture beside.

Technology #4 is a development from scratch, starting from TRL 1 and has reached TRL 6 since the prototype has been successfully installed in an offshore turbine blade, located close to Levenmouth (UK).



The other technology, technology #5, is based on a development to monitor moisture with a fibre optic sensor. This technology is patented by TNO and within this specific project it was explored if it could be used to monitor blade erosion, more specific erosion of the leading edge of the blade which suffers the most from rain droplet erosion. This technology has been further developed from TRL 3 (Proof of Principle demonstrated in the laboratory) until TRL 5 since the product has been tested under realistic conditions in the laboratory, both at TNO and at ORE catapult when running accelerated rain droplet erosion tests.

2.2 Progress realised

2.2.1 TNO - technology #4: Cross Sectional Shear Distortion Sensing (CSSDS)

Cross Sectional Shear Distortion (CSSD) is an indicator for the deformations a wind turbine blade experiences during operation. In the context of this project it is measured as the length change of the two diagonals of the rear box of one (specific) blade at certain distances from the blade root of the Levenmouth Demonstration Turbine (LDT). The diagonal length change is expected to be less than 30 mm by the work package partners.

For illustration a cross section (at R14) is depicted in Figure 1 below.

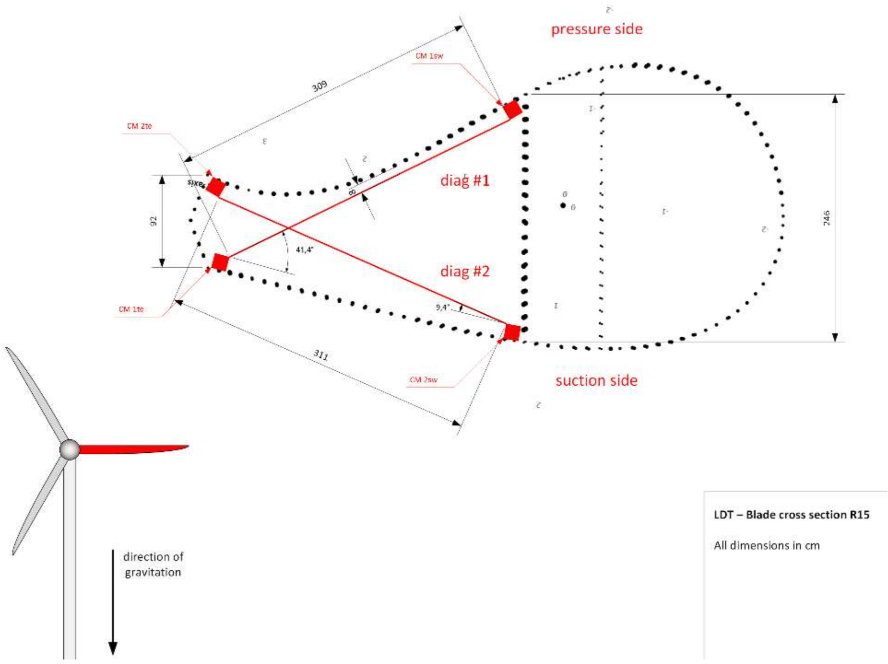


Figure 1 - Cross section R14 of LDT

To determine the length of the cross sectional diagonals, TNO developed the CSSDS based on its Fibre Bragg Grating (FBG) technology and is designed such, that it can measure the diagonal length change of the specified cross sections with an accuracy and precision of below 0.5 mm over a period of operation of 12 months. Also it has to be able to be installed and decommissioned by trained technicians and comply to the requirements of the LDT.

The two most complex components that had to be developed for the CSSDS are the Fibre Corner Mount (FCM) and the Hub Cabinet (HC) and are therefore briefly discussed subsequently.

The main purpose of the FCM is to transfer rear box deformation into the sensing optical fibre to pick up upon the strain along the diagonals. Therefore it has to:

- Provide a robust and rigid interface to the blade surface;
- Clamp the sensing optical fibre without slip and not exceeding the minimal bend radius of 15 mm;
- Apply a well-defined pre tension to the fibre, such that the fibre can also measure compression of the rear box diagonals;
- Be able to be installed simply and safely by dedicated wind turbine technicians (project partner).

One FCM is placed in each of the 4 corners of the 3 designated cross sections of the rear box as depicted in Figure 1 symbolized by red cubes. Although the CSSDS sensor is developed by TNO, it had to be installed by dedicated trained wind turbine technicians in a wind turbine that is managed by ORE Catapult and its contractors.

The separation of tasks and responsibilities inherent to this construction and the fact that it will be a first time right installation form a risk for the installation and operation of the CSSDS that is mitigated by a test integration of the CSSDS into the blade test rig at DTU.

There the complete CSSDS system was installed with two cross sections of the blade equipped in November 2017. The test integration (see Figure 2) resulted in an improved installation manual, training the offshore technicians and confidence to be able to integrate the CSSDS successfully into LDT with the estimated effort.

Figure 2 - CSSDS test integration at DTU, installed FCMs inside the blade (left) and test rig (right)

The complete CSSDS system was installed with two cross sections in August 2018.

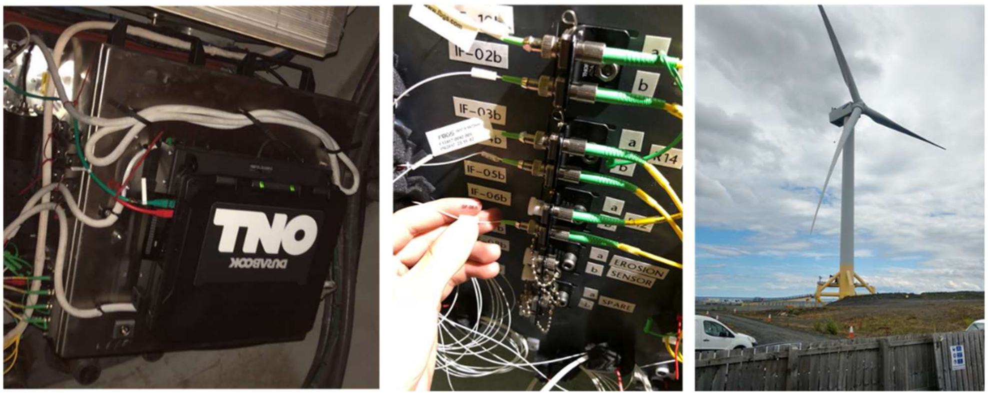


Figure 3 – Overview sensor components during integration of the CSSDS in the Levenmouth turbine

In the figures below the output is shown of the CSSDS. The first picture, Figure 4 is a zoom-in of the wavelength shift during start-up. The wavelength shift can be translated into strain and this is shown in Figure 5 for two diagonals at two cross sections.

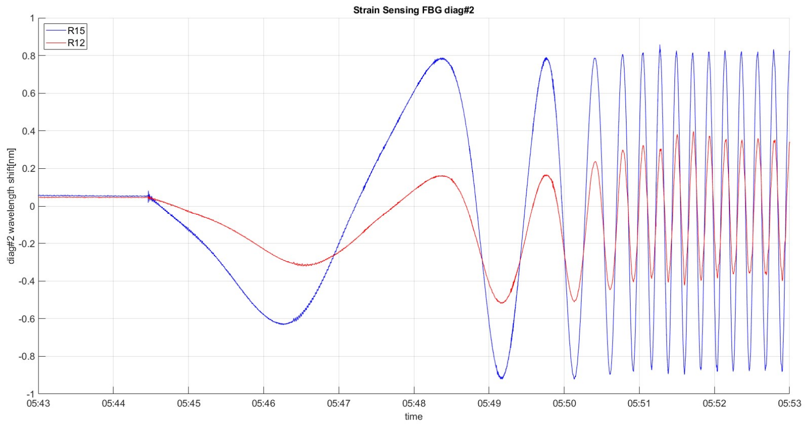


Figure 4 - Zoom into above example data for turbine startup at about 5:45 on 31.07.2018

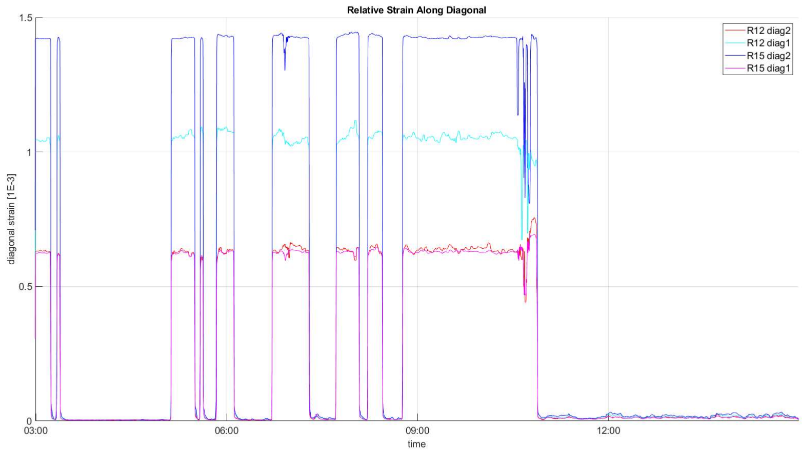


Figure 5 - Derived strain data for above example data for all diagonals on 31.07.2018

In the figure below the diagonal strain is shown for diagonal 2 at location R15, for wind speeds varying from 5 up to 14 m/s.

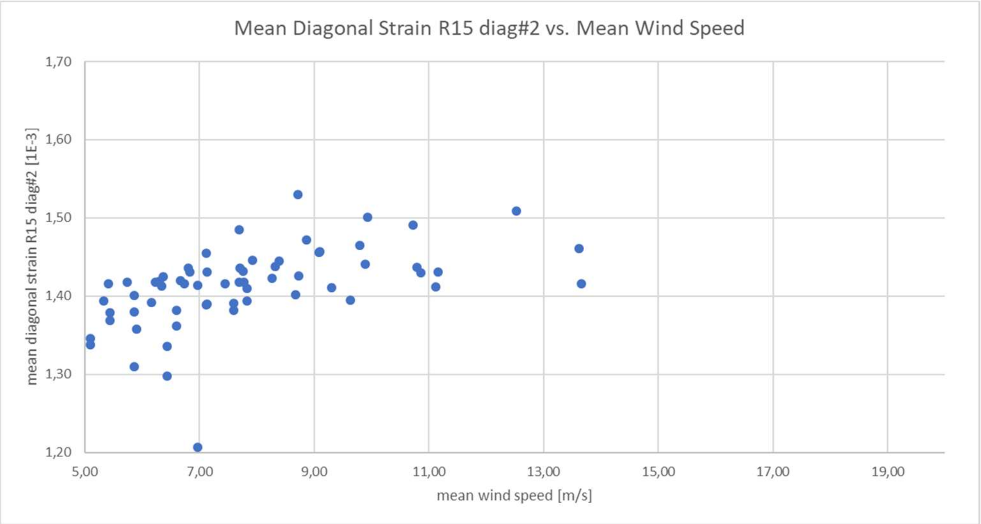


Figure 6 - Measured mean diagonal strain of diagonal #2 at R15 vs. mean wind speed

2.2.2 *TNO - Technology #5 – Leading edge erosion sensor*

The main principle opted for measuring erosion is based on humidity sensing. In previous projects, TNO successfully developed a humidity sensor based on optical fibre technology. More specifically, Fibre Bragg Grating based fibres (FBGs) with a moisture responsive coating were used for this purpose. During the current project, the integration of these fibres in leading edge protection (LEP) coatings of windmill blades is investigated.

The mechanism of erosion detection using humidity sensors is based on a difference in response to the externally changing humidity conditions. For a non-eroded coating, a slow response of the sensor is expected, since moisture transport through a high quality coating progresses slowly. For an eroded coating, suffering from weight loss (thickness reduction) and / or microcracks, moisture transport is much faster, leading to a fast sensor response.

In order to study this principle for LEP coatings, two main questions needed to be answered:

1. Is the mechanical stability of the fibres in the LEP coating sufficient to perform measure erosion? Especially so, since significant droplet impact forces act on the coating (and the fibre).
2. Are the formulation, moisture transport and mechanical properties compatible with the moisture sensing fibres to function as an erosion sensor?

To determine the mechanical stability, TNO supplied erosion sensor fibres to the ODB consortium partner Aerox. The fibres were in integrated various testing coupons and submitted to rain erosion testing. In addition, the mechanical properties of the fibres were shared with CEU, who used these data to run mechanical simulations.

Initially, humidity test were done with TNO fabricated PUR coatings to study the proof of principle. Next, the functionality of the rain erosion sensor inside the AEROX LEP coating was studied. In order to do so, various test samples were prepared at Aerox in collaboration with TNO (Figure 7), after which humidity test were done at TNO with these samples. Finally, rain droplet impact was simulated experimentally at TNO, to relate the droplet impact energy to the response of the fibres incorporated in the Aerox samples.

Figure 7 - Incorporation of TNO sensor fibres in Aerox coatings at Aerox laboratories Valencia.

The rain erosion test (analysed by Aerox) as well as the simulations done at CEU, indicated that the top part of the blade, within the LEP coating, is not a good position for the fibre from a mechanical point of view (denoted as position 1 in Figure 8). Large mechanical stress is exerted on the fibres incorporated in the top part of the blade, possibly leading to failure of the fibre. In addition, the erosion of the LEP was significantly accelerated in presence of the fibre (at position 1). This is probably due to the mismatch in mechanical properties between the LEP coating (rubber-like) and the fibre (stiff, glass-like).

Because this issue was anticipated for at the start of the project, other fibre positions were studied as well, as shown in Figure 8

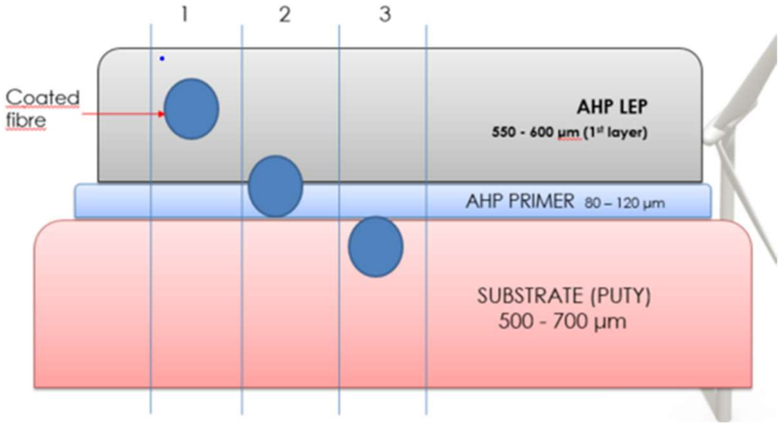


Figure 8 - Fibre positions denoted as 1 (LEP), 2 (primer) and 3 (putty) tested with rain erosion tests (Aerox), mechanical simulations (CEU), humidity (TNO) and rain droplet impact experiments (TNO). **Figure courtesy Aerox.**

The erosion tests indicated that position 2 was significantly better, although the presence of the fibres at this position still accelerated erosion, but at lower rates as compared to position 1. In this respect, position 3 was found to have the least influence on the erosion rate, implying that this is the best position to place the fibres to leave the LEP coating intact.

Mechanical simulations indicated position 2 and 3 are both much better to prevent the fibre from breaking, since the mechanical stress on the fibre is predicted to be significantly lower.

The initial humidity test with TNO fabricated PUR coatings indicated that the principle of erosion sensing in PUR coatings was feasible. Depending on the thickness of the coating present, humidity signals differed due to a difference in moisture transport, implying that the erosion measurement is possible with this approach. This is shown in Figure 9 where the humidity response is shown when embedded in the Aerox LEP coating.

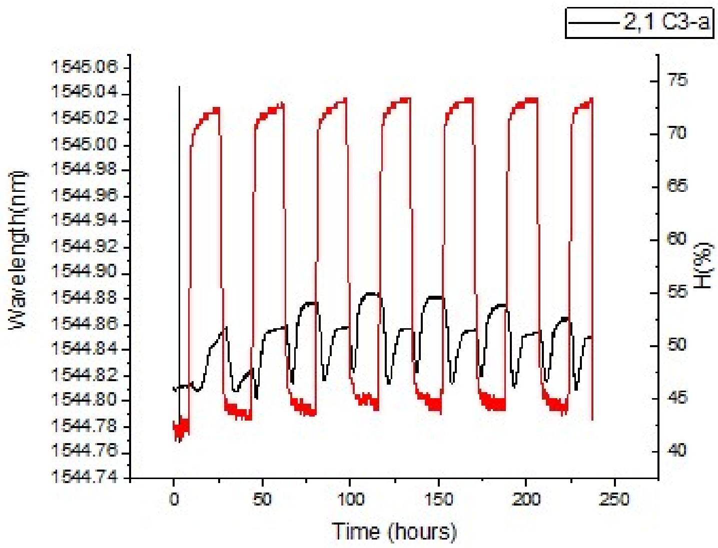


Figure 9 - Fibre response (black line) incorporated in Aerox coatings at position 2 (primer) while varying the humidity (red line) between 45 and 75% relative humidity.

Based on the mechanical stability and functional sensing aspects studied during this feasibility study, it can be concluded that this principle is feasible for erosion testing. However, care should be taken at which position the erosion sensor fibres are placed inside the coating on the windmill blade. For mechanical stability, the deeper the fibre is embedded, the better the mechanical stability of both fibre and LEP coating.

During this study, initially the best position to for the erosion sensing was found to be in the middle (position #2) and in the figure below the results are shown when embedding a fibre at position 2 and 3 and without any fibre.

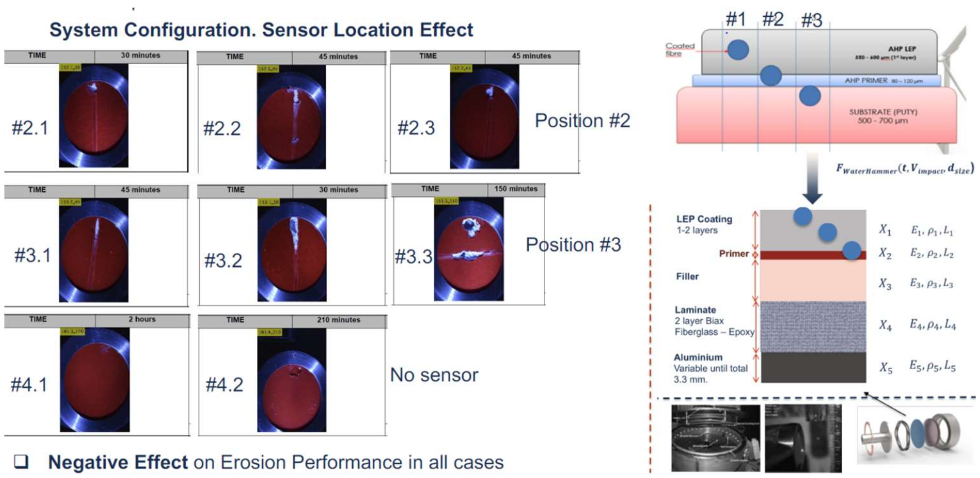


Figure 10: Test runs on the accelerated rain droplet erosion test setup analysing the effect of fibre optic sensor location.

Although erosion is accelerated at position# 2, it does allow for erosion sensing based on humidity signals. In addition, this position is more likely to ensure the fibre does not break during droplet impact and it allows for tracking the number and (low) energy of droplet impact(s).

During the last stage of the project, alternatives were screened (with the help of CEU) in the form of different fibre materials to be implemented in the middle position. Especially polymer optical fibres (POFs, suc as PMMA and PUR) were investigated, since these materials show a better match, in terms of mechanical properties, with the flexible LEP coating. Although a slight improvement in mechanical stress distribution was predicted, the use of POFs would probably not prevent the acceleration of the erosion. Hence, the only way forward seems to be to implement the fibres deeper into the structure, underneath the LEP and primer, but initial studies made clear that sensor response isn't good enough. For that reason the Aerox LEP coating has been put on the offshore wind turbine blade in May 2019, but without TNO's fibre optic erosion sensor.

3 Realised contribution

3.1 Knowledge and technology

The DEMOWIND project developed two novel fibre optic monitoring system with the overall aim to reduce LCOE costs. For TNO it was an important project since it was an enabler to develop two TNO technologies up to TRL 5 and 6. In most of the other projects we reach a lower TRL since we are not allowed to enter an offshore wind turbine. In this project the offshore wind turbine was made available by the consortium leader ORE Catapult from the UK. The project itself did not result in new Intellectual property but the know-how and experience gained is of great value when addressing the monitoring challenges defined in the Product Market Combination (PMC) smart offshore structure within the TNO unit Building Infrastructure & Maritime (BIM).

3.2 Market position

The DEMOWIND project contributed in introducing and maturing novel Structural Health Monitoring (SHM) concepts that could be used for turbine blade monitoring of load and damage for;

- Wind turbine operation (Structural Health Monitoring);
- Wind turbine optimization (pitch control).

In this project, the cross sectional shear has been quantified which results in damage of the blade if the shear stress becomes too high. For the offshore demonstration blade turbine the measured shear is lower than expected and calculated.

The CSSDS has gained interest from the market and is currently considered to be applied in an onshore turbine blade to validate the performance of a newly designed blade.

3.3 Future project

A future project might focus on:

- Further maturing the CSSDS to a product commercially available;
- Applying fibre optic sensor to measure droplet impact and number at a location that doesn’t harm the LEP or top coating;

4 Publicity

4.1 Presentations

1. T.H. (Rob) Jansen. Sensors and sensor networks for smart structures – ISN 2019 Ahoy Rotterdam, January 2019. https://www.ndt.net/article/ewshm2018/papers/0138-Loendersloot.pdf.
2. F. (Fernando) Sanchéz (Universidad Cardenal Herrera-CEU, CEU Universities) & co-authors J. (Jonathan) van Ham & T.H. (Rob) Jansen TNO, Analysis of top coating performance in the Integration of fiber optics sensors for leading edge erosion monitoring - Turbine Blade Manufacture conference, December 2018.

4.2 Conference papers

1. F. Sanchéz & co-authors, Analysis of top coating performance in the Integration of fiber optics sensors for leading edge erosion monitoring - pending

4.3 In- and external technical reports & publications

Internal

1. Design report 'Cross Section Shear Distortion Sensor'
2. Hazard & Operability Analysis 'Cross Section Shear Distortion Sensor'
3. Design report 'Erosion Sensor'

External

4. ODB Midterm Report for the European Union, April 2018
5. ODB End Report for the European Union - pending

Publications

6. Offshore Industry 'Smart Turbine blades', OSI VOL. 12 ISSUE 3 | 2019