

Condition Monitoring

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**RENEWABLE
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WIND TECHNOLOGY



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CUTS MAINTENANCE COSTS**

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BLADE DESIGN

By Chris Hardee

HIGHER OUTPUT AT LOWER LOAD

NEW WIND TURBINE BLADE DESIGN VALIDATED BY MODELLING

Sweep-twist blade designs could yield up to a 20% reduction in fatigue loads while simultaneously delivering a 12% increase in energy captured.



Sweep-twist adaptive rotor (STAR) prototypes were installed on a Zond 750 kW turbine at the TerraGen wind site in Tehachapi, California. Of note are the aft sweep of the tip and the trailing edge curvature. MD Zuteck

Wind turbine blades' basic physics and economics are relatively simple. For one, their power output is roughly proportional to the square of blade length. This relationship pushes designers to create increasingly longer blades for harvesting additional energy. Secondly, as blades get longer, weight increases – by about the cube of the length – which raises raw material costs. This correlation sends designers in search of weight-efficient geometries that are strong and rigid enough to weather the increased loading inherent in longer blades.

Navigating a maze of engineering challenges such as these can lead to interesting design directions. At the US Department of Energy's (DOE) Wind Energy Research Program at Sandia National Laboratories, one result has been the development of a sweep-twist adaptive rotor (STAR).

This curved blade was proposed in earlier theoretical research and has been garnering increasing interest for use in utility-scale applications. The new configuration is seen as a way to reduce operating loads on ever-lengthening blades. If successfully commercialised, the outcome could be larger, lighter, less expensive and more productive wind turbines.

In 2004, Knight and Carver (K&C) Wind Group, a San Diego, California-based wind turbine blade manufacturer, was awarded a DOE contract to develop STAR. Partnering with Sandia, K&C was responsible for design, fabrication, testing and evaluation of a sweep-twist prototype. The firm began by assembling a team of specialised companies and academic institutions, one of which was Seattle-based NSE Composites, brought on board to perform the finite element modeling (FEM) required for the new design.

'NSE had done a lot of analyses over the years on composite aircraft and helicopter aerostructures for companies such as Boeing,' says DM Hoyt, one of the company's founders. 'Plus, we were already troubleshooting another blade problem for K&C.'

Hoyt and his partners at NSE had been using Abaqus from SIMULIA, the Dassault Systèmes application for realistic simulation,

BLADE DESIGN

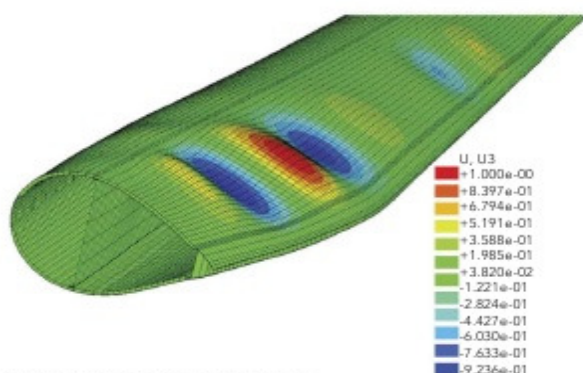


Figure 1. Potential buckling near the blade root.
NSE Composites

as their finite element analysis (FEA) tool. 'Simulation has been a great asset for both our aerospace and wind energy work,' says Hoyt. 'It enables us to explore new ideas and look at the performance of multiple designs and materials while minimising expensive testing.'

Sweep-twist blade basics

Rather than a traditional linear profile, a sweep-twist blade has a distinctive gently curving tip (or 'sweep') with curvature towards the trailing edge. Theoretically, this shape allows the blade to respond to turbulent wind gusts through a process of controlled twisting and bending. As the blade twists, it sheds loads that would normally be translated as material stresses to the root (or base) of the structure. In nature, a similar sweep can be seen in the wing shape of birds that migrate long distances and in the characteristic profile of cetacean tails and dorsal fins.

The engineering upside of twist-coupling is the ability to create longer wind blades while avoiding the higher loads that typically accompany increased length. Reducing loading enables a lighter blade design with lower raw material costs and helps lessen fatigue stresses on the rotating machinery. In early calculations, the STAR design promised a decrease in fatigue loads of 20% using a 3° tip twist. But as the design progressed, longer blades that capture more energy with no increase in load were pursued.

Beyond the potential advantages of altering the traditional length-weight-cost relationship, twist-coupling is seen as a financially attractive solution for tapping low windspeed sites (defined as having an average velocity of 5.8 metres per second at a height of 10 metres). These sites – in contrast to the high wind speed locations that have been the focus of wind-mining to date – are more abundant and typically closer to major power-load centres. If the cost benefit proves favourable, development of low-wind locations could, for example, increase potential domestic wind farm area in the US by a factor of twenty.

Understanding turbine behaviour – without the wind

'Over the years wind blades have become more and more high tech. The industry is pushing the limits of design and materials,'

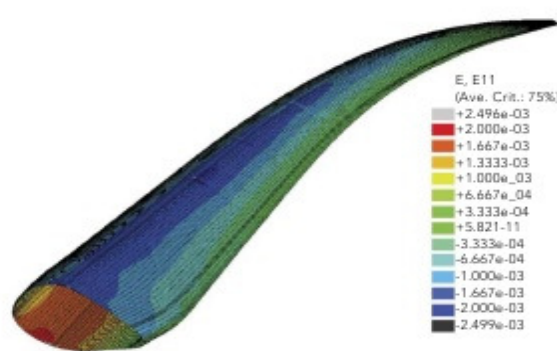


Figure 2. Stress/strain results for the STAR blade prototypes. Note the compression stresses on the upper, or low-pressure, side of the airfoil as the blade bends.
NSE Composites

says Hoyt. 'As that happens, engineers need to tighten up the loose legacy tolerances and manufacturing controls that originated in boat-building technology and adopt the more rigorous analyses that we have always done for complex aerospace structures.'

Of particular use in wind blade analyses with FEA, notes Hoyt, is Abaqus' ability to handle composite properties and control material orientation. It can calculate blade-tip deflection (to avoid 'tower strike') and accurately predict both torsional response (including twist angle, which is key to load-shedding) and shear-compression buckling stability (associated with sweep-twist) of composite sandwich structures.

An additional capability key to wind blade analysis is the extraction of accurate equivalent beam properties directly from a solid 3D FEM. These bending and twisting definitions are used in wind-blade-specific dynamics codes to predict the overall performance of the turbine.

'During the preliminary design phase, the type and amount of input data is often limited,' says Hoyt. 'In the wind projects we've been involved with to date, there hasn't been a high-fidelity CAD model available to use as a basis for the FEM.' So at the start of the STAR analysis, the NSE team only had the blade's basic geometric parameters – the planform shape, the airfoils, and the chord lengths – to work with. The desire for high-fidelity FEA at a design stage when only the basic parameters of the blade have been defined led to the development of NSE's bladeMesher software, which is able to create a solid 3D mesh of the blade from the partial data.

'Our software splines the geometry defined at several locations on the outer mould layer (OML) of the blade and combines it with the composite material thicknesses specified at each location to generate a mesh with the true thickness details,' says Hoyt. 'This solid mesh and material definition is then imported into Abaqus to perform a detailed finite element analysis.'

'We have found that a solid FEM has many advantages over shell element FEMs, which have traditionally been used for blade analysis. These benefits include a more accurate prediction of twisting behaviour and the ability to analyse stresses in the adhesive joints between structural elements,' adds Hoyt.

BLADE DESIGN

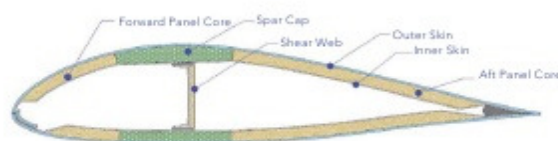


Figure 3. Cross-section of the prototype sweep-twist blade airfoil showing major composite construction features

NSE Composites



Figure 4. The unidirectional composite fabrics follow the curvature of the blade.

NSE Composites

As the design of the blade progressed, the team explored new airfoils and made adjustments to the sweep geometry to hone in on the optimal amount of twisting.

To determine whether the sweep-twist geometry would shed loads as predicted, two wind scenarios were applied to the model: an operating load and an extreme-wind conditions case – 50-year gusts at 156 miles/hour (251 km/hour). The analysis was used to predict the blade deflection and twist, perform detailed stress calculations, and investigate potential shear buckling due to the increased twist inherent in the design (see Figure 1: page 5). For normal loads, there was excellent agreement with the tip deflection results from the section analysis. For extreme wind cases, strain value comparisons were also good. In further detailed studies, the engineering team found that their design met critical buckling limits at more than five times those of extreme wind conditions – a large margin of safety driven by the fact that stiffness to limit deflection, rather than ultimate material strength, was the key structural criterion (see Figure 2: page 5).

Static physical testing of prototypes – for shear strain, blade deflection, and twist angle – followed FEA. The static test verified twist response under operating load conditions. Using fatigue testing, the K&C team was able to validate a 20-year lifespan for the new design.

The prototypes were also field-tested, generating extensive data (as well as power) for several months in Tehachapi, California – site of the TerraGen commercial wind facility and also one of the largest wind generation areas in the country.

A snapshot of STAR's composite makeup

At the STAR project's outset, total rotor diameter for the

prototypes was set at 56 metres. Like most commercial blades, the STARs were to be fabricated using fibreglass and epoxy. Composite design included a stressed-shell approach in which the top and bottom shells are connected by a single shear web, rather than the more typical double web construction (see Figure 3). As the design went through numerous iterations over the course of the project, specific composite materials were carefully chosen for each blade feature.

In the sweep-twist blade design version that NSE analysed with Abaqus FEA, unidirectional roving was called out for the blade's spar caps, and double-biased fabric covering a balsa core was the choice for the shear webs and shell panels. For the skin, a mix of dual-biased and spanwise-oriented (along the length of the blade) unidirectional fabric was selected during preliminary design tests for its ability to follow the curvature of the blade during fabrication (see Figure 4). This combination increased the overall stiffness-to-weight ratio of the blade while improving torsional response – a key factor in the twisting and load-shedding capability of the design. The maximum curvature at which fabrication and layup would become problematic from a material standpoint was also investigated.

A simple twist with major industry implications

With simulation and testing complete, the sweep-twist design's promised load-shedding response resulted in what Hoyt characterises as a 'very impressive' 12% power output boost over similarly-rated turbines now in operation – without load increase.

'I think it's the future of blade design,' says Hoyt. 'People are actively pursuing it.' GE and Siemens, two of the biggest players in the industry, are currently developing swept blades. A start-up, Zimtar – founded by researcher Mike Zuteck, who first conceived the sweep-twist design – won a US\$4 million contract with the DOE to pursue the technology for bigger offshore wind turbine installations.

However, some questions remain regarding scaling of the technology to rotor diameters of 50–60 metres typically seen offshore.

At the fifth Sandia Blade Workshop (in spring 2012), engineers discussed possible downsides. Will torsional loading due to sweep introduce other problems like new modes of aeroelastic flutter? Or will it produce too much fatigue stress in the adhesive joints? There may also be issues on the manufacturing and transport side stemming from the harder-to-handle curved shape, says Hoyt. 'But I wouldn't be surprised if in 10 years a lot of production wind blades had some sweep in them.'

With savings in design time, reduced testing and potentially increased power output, this new twist on traditional design could be a big win for wind.

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TURBINE TESTING

By James Lawson

ASSESSING RELIABILITY

LATEST INNOVATIONS IN WIND TURBINE TESTING WORLDWIDE

Facilities around the world are innovating in testing procedures for reliability, performance and validity. We take a look at the latest in testing centre technology and procedures.



To complement laboratory work, Spain's CENER hosts many other testing, design and analysis services, and also runs a test wind farm offering high-speed winds that can take turbines up to 6 MW. CENER

Reliability is the key attribute of a turbine today, particularly offshore. There are many other important measures of wind turbine performance, notably the cost per unit of electricity generated, but they count for little if a turbine breaks down. And how do you investigate reliability? Test, test some more – and then test again.

Besides reliability, wind turbine testing proves a new design's validity and shows how well a sub-system – or the complete turbine – actually performs in practice. Testing component-level performance and reliability is also vital: accurately predicting the lifespan of critical elements like main bearings or generators allows operators to plan servicing and replacement throughout a turbine's lifetime.

Manufacturers have long had their own test facilities, but there are significant innovations at independent third-party sites. The borders can often blur: centres such as the Fraunhofer Institute frequently work on long-term research projects with businesses and their investors, while Sandia's new test site at Lubbock, Texas features both academic and commercial partners.

Independent centres can offer very large or very specialised equipment. And they can also be seen as impartial – which is crucial for project developers, increasingly focused on the reliability of the equipment that underpins years-long, multi-million-dollar investments. 'There is a huge expansion of wind power and a recognition that to put the next generation of turbines offshore, you need to prove them first,' says Jim Tuten, project manager for the Wind Turbine Drivetrain Test Facility at North Carolina's Restoration Institute. 'The capital backers of these projects also want some assurances. Testing allows you to exercise the unit to its capacity in controlled conditions and without being at the mercy of the wind.'

As well as services ranging from design assistance to electrical testing, these facilities have three main offerings: blade and drivetrain testing – and longer-term turbine trials at outdoor sites that offer grid connections – monitoring equipment and meteorological masts.

Blades are delicate composite structures but face extreme cyclic loads over 25 years or more. Their failure can have severe repercussions in safety, downtime and public image. If many turbines need to be retrofitted, significant costs arise. So validating a blade's design, its manufacturing process and reliability over time are essential to the success of manufacturers, developers and the industry as a whole.

Standards such as IEC-61400-23 or the UK's ISO-17025 accreditation govern the full-scale structural testing of rotor blades. To measure specific stresses and strains, and to map blade properties such as static deformation, ultimate strength, fatigue performance or deformation at resonant (Eigen) frequencies, testers employ various methods such as

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static, single-axis loading of blades at different points along its length or multi-axis, dynamic loadings that better mimic the complex forces found in real life applications.

A full endurance (fatigue) test applies 20 years or more of cyclic loads and might take three to four months, while a static (ultimate strength and resonance) test takes one to two weeks. Applying huge forces and measuring the results demands investment in expensive apparatus such as vibration actuators and linear variable differential transformer (LVDT) equipment that centres must constantly upgrade. In its literature, the Fraunhofer Institute quotes €300,000 – €400,000 for a four- to six-month comprehensive blade test. But as Dr Arno van Wingerde, head of Fraunhofer IWES Competence Centre Rotor Blades, points out, 'compared with a failed wind turbine, that's a bargain'.

Higher power and more comprehensive drivetrain testing is the other main area of development at independent testers. HALT (Highly Accelerated Life Tests) subjects drivetrains to accelerated wear environments to swiftly confirm design and component integrity, and there's a shift underway to test whole nacelles rather than individual components. Drivetrain testers can also be applied to other types of generator or gearbox, such as those used in tidal or wave turbines.

'The wind energy sector is still striving to get a full understanding of integrated testing and the drivetrain has to be investigated particularly carefully,' says Dr Jan Wenske of Fraunhofer IWES. 'Gearbox, generator/ converter system and pitch system failures are currently the main cause for downtime. Increased reliability of the drivetrain leads to a higher energy output, lower O&M costs and thus to an increased profitability of expensive offshore wind parks.'

Today, Clemson University's Restoration Institute in South Carolina is spending nearly \$100 million to build one of the world's largest drivetrain research facilities. A unit capable of testing at up to 7.5 MW will be ready by early next year, while a second, even larger, tester will follow, capable of testing turbines that can generate up to 15 MW. 'The facility will implement new, advanced equipment to simulate blade forces at force and power levels unavailable anywhere else,' says Project Manager Jim Tuten. 'The centre will provide for electrical system testing as well so that combined mechanical and electrical issues can be addressed.'

Renk Labeco's 7 MW and 15 MW test rigs break new ground in how they mimic the forces exerted on the drivetrain by the rotor. Power from the gearbox output is fed into a hydraulic load application system – a load disk mounted on the test stand's central shaft. Radial and axial loads are applied to the disc by 72 hydraulic actuators to simulate real-life, three-dimensional forces and bending moments that gearboxes and generators must withstand. 'The biggest challenge for the project is that we have equipment under design to test equipment that hasn't been designed yet,' quips Tuten. Capable of low voltage ride through (LVRT) and zero voltage ride through (ZVRT) testing, the lab will also examine generator grid compatibility. Future plans include a 15 MW hardware-in-the-Loop (HIL) capability that will aid testing of other types of electrical equipment as well as ever-larger generators.

The Wind Technology Testing Center (WTTTC) in Charlestown, Massachusetts is the other sizeable stateside development. Overseen by the Massachusetts Clean Energy Center (MassCEC) and its partners, the WTTTC opened in May 2011 and offers three test stands, each of

which can handle blades up to 90 metres. 'This is the world's largest structural testing lab for blades, and it's the only one in the USA,' says Executive Director Rahul Yarala. 'We're extremely busy with blade testing and are working closely with manufacturers and developers.'

Capable of exerting forces of up to 84 MNm, WTTTC offers the full suite of certification tests along with the latest blade prototype development methodologies, R&D partnerships, blade repair capabilities and hands-on workforce training. Fatigue tests employ the National Renewable Energy Lab's (NREL) patented resonant test system technology. As well as the WTTTC, NREL's smaller-scale National Wind Technology Center still offers blade, drivetrain and many other types of testing, research and development for turbines up to 5 MW. The WTTTC also proves that test centres can act as hubs for further investment: TPI Composites has opened a blade R&D centre and prototyping factory 74 km south of Charlestown. TPI will be a WTTTC customer, and cited it as key to its decision to set up shop in Massachusetts.

EUROPE HAS THE LARGEST SPREAD OF TEST FACILITIES BOTH IN OPERATION AND UNDER DEVELOPMENT

Another new wind turbine blade-testing facility is planned for Clarkson University, based in Potsdam, New York, this time focusing on smaller blades in the 12–15 metre range. The Center for Evaluation of Clean Energy Technology will be built and run in conjunction with other partners by London-based Intertek plc, using a \$4.2 million grant from the New York State Energy Research and Development Authority.

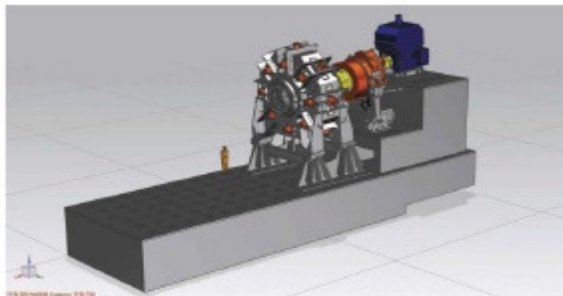
Still on the East Coast, Poseidon Atlantic in Northampton, Virginia, will offer sites for turbine prototype testing, infrastructure, wind measurements and wind turbine testing and certification services. The site is planned to hold between five and ten turbines, with a maximum size of around 5 MW. The owners expect to start construction in late 2013, with the first turbines online before the end of that year.

Asia's only independent test centre is SGS Wind Energy Technology Center (WETC) in Tianjin, China. Opened in June last year, this focuses on full-scale blade testing for blades up to 70 metres long. The centre offers natural frequency, static, fatigue and ultimate static tests as well as a full range of other consultancy and solutions such as blade-specific non-destructive testing and composite technology training.

As befits the current world leader in both installed wind capacity and turbine manufacturing, Europe has the largest spread of test facilities both in operation and under development. Germany's Fraunhofer Institute opened its new Competence Centre Rotor Blades testing facility in Bremerhaven last year. As well as several beam test rigs and material climate chambers, the centre's two test rigs can handle blades up to 70 metres and 90 metres respectively. The 90 metre rig – a giant 1000 tonne block of steel – can load blades along their length to a maximum of 1800 kN and bend them by up to 30 metres. Uniquely, it allows the blade to be tilted too. To cope with demand, another test rig for 50 metre blades will go into operation this year.

The latest development here is the DyNaLab (Dynamic Nacelle Laboratory). When active in 2014, it will have a drive output of 10 MW and will be used to test complete nacelles ranging from 2 MW to

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Renk Labeco's 7 MW and 15 MW test rigs break new ground in reproducing the forces exerted on the drivetrain by the rotor.
Clemson University Restoration Institute

7.5 MW. A 40MVA artificial grid will allow complete electrical certification of test turbines, and the institute is currently working to scope the test stand's final specification. There are also plans for a new lab for foundations and support structures at Fraunhofer's Hannover location. 'This facility gives us the possibility to test the dynamic behaviour of the complete structure with near-realistic simulation of soil/seabed-support structure interactions,' says Dr Jan Wenske. A medium voltage lab, a pitch-system test bench and a mainshaft lifetime test bench are also under development, he adds.

Fraunhofer is looking to build further turbine test sites, he says. Germany already has the DEWI test site near Wilhelmshaven, currently holding ten prototypes totalling over 19 MW, while a new site in Janneby, Schleswig-Holstein, will open at the end of this year. Developed by GL Garrad Hassan and two partners, Janneby will have eight test locations suitable for turbines up to 150 metres in height. Users will be able to access services that include wind, acoustic, power performance, load, power quality and LVRT measurements. A LiDAR test site is also planned.

The Netherlands hosts Europe's largest testing site in Lelystad, where the first turbine started operations in June last year. Operated by Ecofys, Lelystad can service ten turbines with tip heights up to 200 metres. The main Dutch testing facility is Knowledge Centre WMC. Able to test blades up to 60 metres long, it has operated since 2003.

Spain's CENER was the world's largest independent turbine testing facility when it opened in 2008. Under one roof, it hosts a full range of static and fatigue tests for blades up to 100 metres, and can test drivetrains of 2-6 MW. To complement lab work, CENER hosts many other electrical testing, design and analysis services, and also runs a test wind farm offering high-speed and high-density (Class 1) winds that can take turbines up to 6 MW. 'The drivetrain lab offers a six-degrees-of-freedom drivetrain testing bench, a torque-only nacelle test bed and a generator test bench,' says Pablo Ayesa Pascual, director of CENER's Wind Energy Department. 'The first two are capable of applying a torque of 6 MNm and all have been dimensioned for 8 MW of main actuation. We see a 12 MW power test bench in the near future, however we have no formalised plan as yet.'

Over in the UK, an investment in the region of £150 million (\$240 million) means the National Renewable Energy Centre (Narec) will soon rank among the top global independent testers. Joining the

existing 50 metre test facility, the new 100 metre blade-testing centre will be the world's largest and should be ready for commissioning by September 2012. The 130 metre-long building will house a single Moog hydraulic blade-testing rig. There will also be 3 MW and 15 MW drivetrain testers; the former is intended primarily for tidal turbines, but could be used for wind too. The 3 MW centre is close to completion while the 15 MW facility is slated for completion by August 2013. The centre already offers a broad spread of services including a dry dock, subsea and electrical testing, and a cold chamber that can drop down to -20C. Narec is also planning an offshore turbine test site at Blyth, Northumberland, for 2014. 'Our USP will be the ability to test on- and offshore at the same time,' says Steve Abbott, Narec's marketing and communications manager. 'We're geared to large offshore turbines and marine facilities, and will have the ability to replay extreme events onshore. Our customers – manufacturers and project developers – want to demonstrate turbines in UK sea and seabed conditions, with learnings that translate to other North Sea locations.'

Turbine testing development in Denmark is focused on the Lindoe Offshore Renewables Center (LORC) in Odense. Still at the planning stage, it will include facilities for welding research, foundation testing and other mechanical testing for lubricants, gears, bearings and oil filters. Innovative 'helicopter testing' will evaluate how blade coatings cope with mechanical strain, UV exposure and chemical resistance, as well as tip and leading edge erosion.

The other big development in Denmark is Risø DTU's new turbine testing field at Østerild in northern Jutland. With space for seven turbines up to 20 MW and 250 metres high, Østerild augments the Høvsøre test centre, which can hold five turbines with a maximum height of 165 metres. Turbulence at Østerild gives manufacturers a wider range of test wind conditions, measured more accurately by 250 metre-high met masts. Advanced grid connection technology will allow greater experimentation, such as checking turbine tolerance to varying grid frequency. Østerild's infrastructure is nearing completion, with two test sites already available and it will host the second prototype of Siemens' 6 MW offshore turbine later this year.

With this rapid expansion of test facilities, manufacturers and developers have more choice in where to develop prototypes and prove new designs. Though centres often form long-term partnerships with manufacturers, a mixture of knowledge sharing and competition between independent providers can only help to raise test standards, and so improve turbine reliability and performance.

'Companies need effective testing to prevent silly mistakes that cost money and affect the industry's reputation,' says MassCEC's Rahul Yarala. 'Of course, there's only so much business out there and every lab needs revenue. That's a good thing: it improves test timing, methods and cost effectiveness.'

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CONDITION MONITORING

By L.W.M.M. Rademakers
and T.W. Verbruggen

Condition based maintenance is increasingly used to curb wind turbine O&M costs, especially offshore. Replacing corrective maintenance with condition-based maintenance cuts downtime while improving the planning of activities and the use of resources and equipment.
Siemens

ACTING IN TIME TO CUT O&M COSTS

FIBRE OPTIC MONITORING

Fibre Optic Blade Load Monitoring (FOBM) can be effective in ensuring that appropriate maintenance gets carried out in a timely manner, according to Netherlands-based research firm ECN.

Condition based maintenance is increasingly used to curb wind turbine operation and maintenance (O&M) costs, especially at offshore sites where visits are prohibitively expensive. Replacing corrective maintenance with condition-based maintenance cuts downtime and damage, while improving the planning of activities and the use of resources and equipment, which reduces costs.

Many systems are already on the market to monitor the health of components. Approaches such as SCADA data, drivetrain monitoring, visual inspections and oil samples are all common practice in wind energy and have proven their added value.

But all these techniques only start providing useful information once components have really started to degrade. As this degradation is strongly related to the loads acting on the components, ECN has been seeking a solution to monitor mechanical loads.

Since most of the loads are introduced via the rotor blades, ECN's development have been focusing on a low-cost method to monitor the blade root bending moments and process the data to help

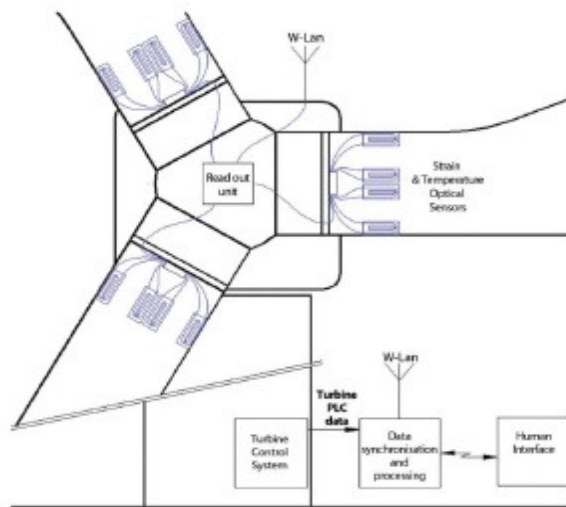
turbine operators decide on issues such as maintenance action to prevent failures, when to postpone or prioritise visits, or whether to extend turbine life.

Features of an FOBM system

The system is based on optical fibres with Bragg gratings to measure the strain in the blade roots. Compared with the copper strain gauges commonly used for measuring blade root bending, optical fibres should theoretically drift less over time and last longer, while providing reproducible data.

Many attempts to demonstrate the advantages of optical fibres for measuring strain in rotor blades have failed. Not only was the technology not mature enough, but the influence of temperature was underestimated, and installing sensors and measurement equipment left turbines at a standstill for too long. Final results looked far from professional and once measurements were finally obtained, it was unclear how to use them – they could only be added to the large

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The structure of the FOBM system

ECN

amount of data already available to the operators. ECN now claims its FOBM system offers the benefits of optical fibre technology without its drawbacks. The system consists of:

- A patented sensor assembly that is easy to install and replace, requires no calibration, and provides reliable, accurate and reproducible strain data over a very long period;
- A commercially available interrogator to read the fibre optic sensors;
- A measurement computer that derives loads data from strain data and combines the blade loads data with turbine power line communication (PLC) data;
- Wireless-LAN to enable communication between the rotor and the turbine base;
- Software for data processing that filters and cleans up the time series, categorises the data per design load case, and provides key figures, statistics, and graphs to the operator for O&M optimisation.

The entire system can be installed by regular maintenance technicians in less than a day and requires no further skills in fibre optics. To measure blade bending moments in flapwise and edgewise direction, four sensors must be installed in each blade root. All four sensors are connected to individual strings that are connected to the interrogator. The measured data can be obtained remotely.

Innovative algorithms for data cleaning and filtering

In general, operators want to know if their turbine operates within its design envelope, so that measures can be taken if necessary. Next, operators want to know if some turbines are more heavily loaded than others, so O&M activities can be prioritised along with analyses of condition monitoring data and inspection results.

ECN has implemented the data analysis as follows. From the beginning, the software starts building up a capture matrix with statistically sufficient data that can be used as a reference data set.

All time series relevant for the capture matrix (which displays results according to load conditions) are stored, for purposes including traceability. The time series are also used to derive fingerprints, envelopes and criteria for rejection. Once the measurement campaign is running, the software detects the load cases (operational modes) present in the 10 minute time series, and splits the time series into single mode files – such as normal operation, start-up, shutdown or emergency shutdown – and filters out erroneous data. Next the software determines statistical data of the single mode files – such as minimum, maximum, mean, standard deviation and equivalent loads – updates the load spectra plots, and analyses the frequencies.

Time series themselves are only stored if they are used for fingerprint information or when the processing is not finished successfully. The software provides monthly reports, giving information about the captured data, deviations from long-term statistics, and a comparison with fingerprint data. Furthermore, the monthly reports contain information about extreme loading conditions and possible errors in the measurement system.

In the longer term, the operator can ask for reports with information about the cumulative loading of the blades and rotor (equivalent loads, fatigue spectra) to monitor the consumed lifetime. This information can be used for comparison with design data or for comparison with data of other turbines.

Statistics

Each month an overview of the performance of the measurement system is generated. This report provides details of measurements over the preceding month and over the system's lifetime.

The data processing performs checks on the data quality, as data might be rejected due to measurement faults or unidentified operational modes. These time series are quarantined for further analysis as required and load results can be adjusted for lost data.

Equivalent loads:

Equivalent loads are calculated for all modes. For stable operational modes such as power production, equivalent loads are plotted as a function of the wind speed. For transient modes, values are plotted for each file. Values should be within limits set for the capture matrix and the plots should enable extreme values to be easily identified.

Load spectra:

To inform users about encountered loads, these are plotted for the relevant month as well as for the equipment's lifetime. For the monthly figures, a reference based upon the capture matrix is used. For the lifetime, an external reference should be used.

This external reference can be chosen depending on the application. For prioritising maintenance, other turbines of the same farm could be used for this reference. When the user is interested in calculating the equipment's theoretical lifetime, a design spectrum outlining the equipment's intended parameters of use is the most obvious choice.

CONDITION MONITORING

Frequency plots (average power density):

Under certain conditions, time series are analysed to examine frequencies, which can reveal changes in the blade's structural properties apparent through shifts in frequency or amplitudes.

Optical Sensor Assembly

The FOBM system requires four sensors per blade to determine the blade load bending moments in both edgewise and flapwise directions. ECN has developed a special sensor assembly for strain measurement in wind turbine blades as a plug-and-play device. The sensor consists of a fibre with a Bragg grating mounted between two studs via a carrier. The studs are mounted on the inner side of the blade root at a distance of 10 cm.

The carrier ensures that the fibre follows the displacements of the studs so the strain in the blade root is measured over enough length to avoid local effects of the blade material. The carrier protects the fibre from sharp bending and also accommodates a second Bragg grating for temperature compensation.

To install a sensor, the technicians glue the studs on the blade with the help of a dedicated mounting tool. After a short curing time, the carrier can be mounted on the studs and the patch cables are plugged in. The carrier with the fibre and connectors is assembled in the factory under well-defined conditions and is already calibrated.

During operation, the sensor provides strain data under both tension and compression with high accuracy (5 $\mu\epsilon$) over a long period of time. Re-calibration is not necessary, because the sensor itself is very stable. If, for whatever reason, the sensor should fail it can be easily replaced. Since all assemblies are calibrated in the factory, on-site calibration is not necessary.

This patented sensor assembly has proven to work reliably, to provide strain data with high accuracy, and to offer easy installation and replacement. The fibre itself has a very high ultimate strain and can easily last a turbine's lifetime. The most critical element is the connection between the blades and the studs. This is chosen for application in existing turbines, although the sensor's design also suits other fastening methods that match blade manufacturing processes.

System architecture

Apart from the sensor and the software for data analysis, the system consists of a commercially available interrogator to read out the fibre optic sensors, a measurement computer that derives loads data from strain data and combines the blade load data with turbine PLC data and wireless-LAN to enable communication between the rotor and the turbine base.

Interrogator:

Interrogators that meet the requirements of wind turbine applications are available on the market, although robustness, price level and performance still require additional development. Several types of gratings can be used, but Draw Tower Grating in combination with a WDM interrogator with three channels is preferred in this application. This approach ensures a robust and stable measurement system, while the disadvantages of wavelength gratings is minor, due a well controlled production process of complete measurement strings. In

Turbines ID:	Month		Lifetime	
	Files	Time [hour]	Files	Time [hour]
Elapsed time		744		39,850
1 Start	20	3	1071	134
2 Power production	4400	700	230,672	36,660
3 Emergency shutdown	2	2	107	98
4 Normal shutdown	18	2	964	80
5 Idling at high wind	10	0	536	11
6 Parked at high wind	5	1	268	27
7 Idling at low wind	50	10	2678	536
8 Parked at low wind	1	2	54	107
9 Waiting for wind	50	1	2678	27
Valid single mode files	4556	719	239,028	37,679
Quarantine	80	25	4258	2171
Time covered	96.6%		94.6%	

Monthly statistics from an FOBM installation

ECN

In this case four different sensor assemblies are sufficient to cover the whole measurement range for one blade, while the configuration for each blade can be kept identical.

Measurement PC:

The measurement PC is a standard device with a Windows operating system. Data is imported from the turbine PLC as well as from the blade load measurement system. The measurement software combines these data, and processes the data which results in single mode files. Based on these files, a database is filled with statistical data, load spectra frequency plots and a capture matrix with fingerprint information. The amount of data to be stored is limited, because the original time series are thrown away after successful processing. Only time series which are used as fingerprint information (capture matrix) are stored in the system.

User interface and remote access:

The user can access the system to retrieve the information required. This can be realised via standard communication provisions. During the development phase, the reporting module runs on the remote computer. For commercial implementation other configurations will be more appropriate.

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ANTI-CORROSION

By Anders Voldsgaard Clausen

PROTECTING POWER FROM CORROSION



DESIGN, SURFACE PREPARATION AND APPLICATION ARE KEY TO LONGEVITY

Many parties are involved in delivering successful corrosion protection for offshore wind turbines. The steel fabricator, paint applicator and paint supplier must all work closely together to avoid the risks of inadequate protection and costly on-site repair work.

Corrosion protection is always the last step during a production process. When a job is behind schedule, there is often pressure on the paint shop to make up for lost time by hastening its part of the production process. But trying to gain time by rushing the painting process can have costly consequences.

Painting offshore structures in a paint shop costs from €15 to €25 per m², depending on the setup of the workshop and the

paint system. The cost of coating repair work performed on site and onshore is about 5 to 10 times more, due to the logistics of getting men and materials to the job site and limited access to structures due to weather conditions. If repair work must be done offshore, when corrosion protection fails prematurely, the cost can increase to more than €1000/m², between 40 and 60 times the cost of doing the job in the paint shop.

ANTI-CORROSION

Onshore exposure implies generally cyclic dew/condensation, with or without minor salinity, and moderate exposure to sunlight, resulting in moderate corrosion at holidays, weak points and damaged areas of the coating system. In contrast, offshore exposure implies long-term exposure to humidity with high salinity, intensive influence of UV light, wave action and the presence of a splash zone area, and high corrosive stress resulting in speedy corrosion at vulnerable areas of the coating system.

This difference in exposure severity is also reflected in the mass and thickness loss per unit surface of low-carbon steel and zinc in the first year of their unprotected exposure. For example, in Germany, the onshore corrosivity is evaluated as being about C3, according to ISO 12944, which corresponds to a thickness loss of 25 to 50 µm. In comparison, for splash zone areas, as much as 500 µm thickness loss has been observed in the first year of service.

Key factors for corrosion protection

A qualified coating system is not enough to guarantee a successful corrosion protection. Certificates and approvals are often overestimated. Indeed, the EN ISO 12944, part 5 (German issue) lists nine factors that are decisive for the durability of a coating system. The coating system itself is only one, and other important factors include the design of the structure (access possibilities), the design of edges and weld seams, the workmanship of the applicator, the specific condition of the steel before surface preparation, and the exposure of the paint system immediately after completing application.

In effect, failure statistics show that the paint system itself is seldom the reason for the premature failure of the corrosion protection. The paint industry is mainly supplying 'half-products': that is, two or more component-reactive resins. It is the applicator who effectively creates a chemically new substance that in the end provides corrosion protection. Failure can occur during this process if the mixing of the components, the temperature control, the time requirements, and the application of the mixture onto correctly prepared surfaces are not all carried out properly. That is why permanent quality control and supervision by qualified professionals are required.

Design considerations

The design and fabrication of steel used in wind turbine construction is critical to its corrosion protection. Before the applicator starts their job, the steel builder has to provide a structure suited to being painted successfully. It is a law of nature that corrosion will always start at edges and weld seams – which is where the responsibility of the steel builder begins.

Coatings can only protect accessible surfaces – a fact often neglected in design. EN ISO 12944, part 3, Design Considerations, recommends that appropriate distances required for tools in corrosion protection work are respected. It also recommends minimum dimensions for openings that provide access to confined areas, minimum dimensions for narrow spaces between surfaces, and the incorporation of design features that may be used to avoid deposits accumulating or water being trapped.

Construction designs that create insufficient access for painting should be avoided. During the fabrication of an offshore steel

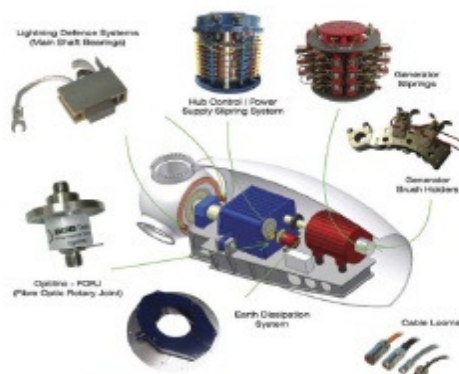
structure, the recommendations of ISO 8501, part 3 (preparation grades of welds, edges, and other areas with surface imperfections) should also be considered. This relatively new standard, which appears not to be well known at engineering offices and steel construction companies, is aimed at the steel builder, not the paint applicator. It gives recommendations about the required condition of the steel surface if paints are to be applied later for long-term corrosion protection.

For offshore structures, preparation grades P2 or P3 should be specified, depending on the relevant details of the structure. This means the steel surface should be free from welding spatters and slags, pores, undercuts and laminations. The surface also needs to be dressed (by grinding) to remove irregular and sharp-edged profiles.

Pores are often found, particularly on welds, and inspectors are often asked if pores can be filled up with paint. Pores should never be filled with paint or filler. The steel builder has to repair them, according to the demands of EN ISO 5813, weld quality B.

Correctly designed weld seams are crucial to successful corrosion protection. Handmade weld seams on offshore structures generally need to be ground by the steel fabricator before they can be painted. Poor weld seam design will cause steel to corrode quickly.

It is often helpful to have something to show to the welder to clarify what is meant by the right design for corrosion protection at a weld seam. The NACE Standard RP 0178, for example, provides



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ANTI-CORROSION



Offshore structures present some of the toughest corrosion protection challenges for coating systems.
Hempel

photographic examples of the front and back sides of good and bad weld seams.

Finally, the steel fabricator has to be careful about the condition of the carbon steel to be used to build an offshore structure. Unpainted steel is characterised by four rust grades according to EN ISO 8501, part 1. For offshore structures, it is strongly recommended to use steel with a rust grade not worse than B (Norsok M501), or not worse than C (EN ISO 12944). The service life of a coating system depends directly on the rust grade of the initial steel and the degree of surface preparation (Sa2 and Sa3 according to EN ISO 8501, part 1).

In summary, the steel fabricator has to be aware that he is constructing an offshore structure that needs certain access and surface conditions for successful corrosion protection.

Surface preparation and paint application

The workmanship of the applicator is very important for a coating system's long service life. Half of all premature corrosion protection failures are application-related; thus all operations must be high quality and quality control checks must be frequent. Correct surface preparation and coating thickness are definitely the most important application parameters. Planning and informing the work crew of the different procedures and, preferably, signing off on the results are necessary to guarantee the right level of quality.

Because offshore structures present some of the toughest corrosion protection challenges for coating systems, the best possible equipment and setup should always be used for painting. Automatic blast facilities should be used to minimise variations in surface cleanliness and surface roughness. Painting booths with climate control and temperature regulation are recommended.

Two-component spray equipment should be used to minimise mixing errors. The foreman and/or supervisor should be qualified and certified according to FROSIO or NACE level 3 or equivalent.

The coating system

Today more than ever, the market for corrosion protection of steel

wind turbine towers is typified by strong competition. Coating application around the clock, under time pressure, carried out by foreign workers with whom communicating can be difficult, are typical aspects of a day of coating work. Demand is increasing for fast-drying, solvent-free coatings, lower thicknesses, and in addition there is a need for fewer coats.

In reality, successful testing and certification for coating systems do not necessarily guarantee successful coating performance. Indeed, it is one thing to apply the very best coating under laboratory conditions onto perfectly prepared test panels and submit the panels for laboratory testing.

Replicating the same results on site, on thousands of square metres of steel, applied around the clock and sometimes under less than optimal conditions, is a completely different matter. The more difficult a coating system is to apply, the higher the requirements during application, and consequently the more challenging the task of the paint applicator.

Coating materials should, therefore, not only be easy to apply, but should also, to some extent, be versatile enough to tolerate the variations in application that occur in daily practice.

Field experience matters

Nothing says more about the quality and performance of a coating system than field experience. Such experiences offshore say much more than any tests ever can.

Only practical experience can demonstrate whether the coating system can be reliably applied daily at different locations, at different temperatures, during all seasons, onto different structures, onto complicated geometry, with low spray dust pickup, with good flow properties, good sag resistance and good thickness tolerances. And, furthermore, only practical experience will tell whether a coating system can even be reliably repaired on-site using standard methods.

However, while long-term experience with a company is the most reliable basis for coating selection when going offshore with its coating solutions, new, unproven coating systems will always be required by an offshore wind industry in constant evolution.

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