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DEVELOPMENT OF A ROBUST STRUCTURAL HEALTH MONITORING SYSTEM FOR WIND TURBINE FOUNDATIONS

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ABSTRACT

The construction of onshore wind turbines has rapidly been increasing as the UK attempts to meet its renewable energy targets. As the UK's future energy depends more on wind farms, safety and security are critical to the success of this renewable energy source. Structural integrity is a critical element of this security of supply. With the stochastic nature of the load regime a bespoke low cost structural health monitoring system is required to monitor integrity. This paper presents an assessment of 'embedded can' style foundation failure modes in large onshore wind turbines and proposes a novel condition based monitoring solution to aid in early warning of failure.

INTRODUCTION

Large scale development of onshore wind turbines as part of a strategy to meet UK government targets has been a result of the Governments obligations to reach European Union carbon reduction targets. Increasing the percentage of renewable energy in the electricity mix, displacing older, fossil fuelled, thermal generation will result in wind energy becoming an important component. The United Kingdom has a target to produce 15% of its energy needs through renewable methods by the year 2020 [1]. In order to meet this ambitious target numerous wind farms have been constructed recently and others are under construction or in planning phases. Ensuring reliability of wind turbine structures allows safe operation and maximum availability.

Wind turbines operate under challenging loading regimes [2] the effects of which could diminish their structural integrity leading to significant remediation costs and disruption to the electrical grid. Current research activities focus on for example structural damage of blades [3]. Structural health monitoring (SHM) provides the means to track the structural condition of turbines throughout their 20-25 year lifecycle [3]. Protecting assets and maximizing power production are challenges and priorities for wind turbine operators.

Over time, the onshore turbine structure will become less efficient and less effective when compared with a new one. This can be caused by numerous factors including environmental exposure, fatigue of blades, tower and concrete foundation, soil settlement, poor construction and poor maintenance. Health and condition monitoring systems are often used on components such as the gearbox but are used less frequently to monitor the state of structural components [4]. There are three main areas where SHM can be applied to an onshore wind turbine: the rotor (including the blades), the tower and the foundation. Each structural component presents different structural problems, failure modes and failure rates.

This paper considers some technical challenges including structural behavior/failure modes of onshore wind turbines and affect on wind turbine foundations. Current health monitoring technologies with potential applications to onshore wind turbines are considered and a novel health monitoring strategy for the wind turbine's foundation with continuous proactive capability is presented. The paper also presents some key research themes to develop a robust SHM technology.

Structural failure rates and an analysis of foundation failure modes are presented. The outcome of a field visit to a wind farm site exhibiting signs of failure is then covered. Finally a novel structural health monitoring system is proposed to continuously monitor the level of failure in the foundation.

1. STRUCTURAL DAMAGE IN ONSHORE WIND TURBINES

Figure 1 shows a usual arrangement of an onshore wind turbine, with blades, tower and gravity concrete foundation. Main types of foundation-tower interface used for large onshore turbines are the ‘embedded can’ and the ‘bolted’.

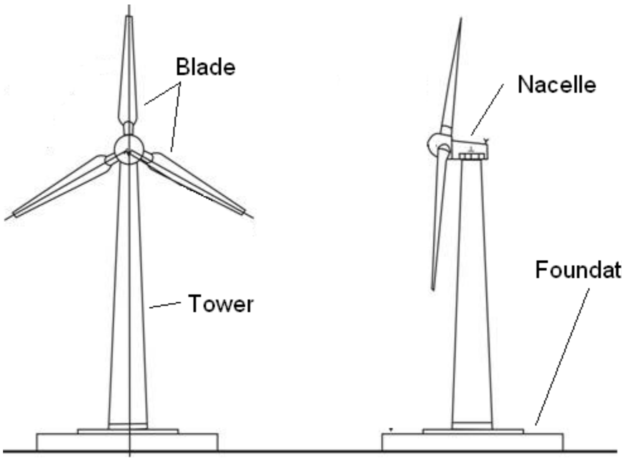


Figure 1: MAIN STRUCTURAL COMPONENTS OF A TURBINE

Current research is focused on structural damage of blades and towers; specific information on the structural behavior of wind turbine foundations however is very limited, in particular there is a lack of in-depth reporting of failures. Tavner et al [5] provides a useful guide to the levels of component structural failure within turbines in several countries. The work shows the blade failure rate including pitch mechanism is between 0.2 and 1.0 per turbine per year, although the average is closer to 0.2. The actual blade failure rate (not including the pitch mechanism) is much lower reaching 0.025 failures per turbine per year as calculated in [6]. A survey effort of more than 1500 offshore wind turbines conducted by the European Wind Energy Measurement and Evaluation Program (WMEP) showed that the blade failure rate is around 0.11 per turbine per year whereas the failure rate of support and housing is about 0.1 failures per turbine per year [7]. The same survey shows that the rate of failure of the nacelle is 0.003 failures per year per turbine and the tower failure is around 0.001. Based on the literature review it was found that the average turbine is extremely unlikely to suffer failure of the tower or the nacelle. However, the chance that of one of the blades could fail during its lifecycle is around 50%. The fragility of the blades and risk of failure is demonstrated by the large amount of research work in that area compared to articles concerning the turbine tower and foundation.

2. DAMAGE MECHANISMS AND FAILURE MODES OF WIND TURBINE FOUNDATIONS

It is unknown how reliable wind turbine foundations are as there is a lack of published data available. Whilst a complete collapse of a turbine is rare, non-catastrophic localized failure of the reinforced concrete elements of foundations appears to be more frequent. Recent studies showed that the structural failures in the tower and foundation account for only a very small percentage of the total number of failures accounting for 1.5% of failures and 1.2% of downtime [8]. Wind turbine foundations are normally subjected to large cyclic moments and forces and if designed incorrectly this could produce structural damage in the foundation and jeopardize the stability of the wind turbine. Problems in the foundation can manifest themselves in a number of ways including deterioration of the underlying fill and ground below the foundation or in the degradation of the reinforced concrete pedestal and base.

Long-term cyclic loading causes the foundation-soil interface to degrade resulting in a reduced rotational stiffness which in return decreases the bearing capacity of the soil. In this case, gravity foundations exhibit large differential movement and can tilt under a high lateral wind load as witnessed by the catastrophic failure of a wind turbine concrete foundation during a heavy storm in Goldenstedt, Nortwestern Germany in 2002 where it appears the eccentric load severally damaged the soil subgrade causing the turbine to overturn (see Figure 2).

Figure 2: GOLDENSTEDT WIND TURBINE COLLAPSE

Figure 3 shows the area where voids can develop in a concrete foundation for embedded can type connections when the turbine is subjected to eccentric and cyclic loading. Water ingress through the damaged concrete-web interface coupled with the movement of the tower can interface acts to exacerbate the level of movement through erosion. The presence of voids around the embedded can allows the whole tower to move significantly in the vertical direction as well as to a smaller extent in the horizontal direction. There has been no published work relating to this type of displacement but movements in the range of 5mm were noted during a site visit with reports of movement up to 20mm on other turbines at the same site.

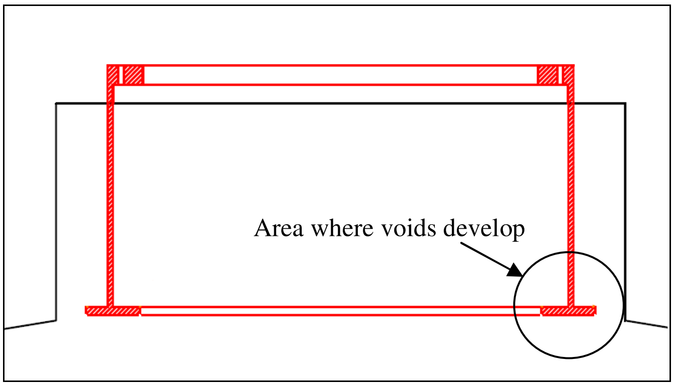


Figure 3: FAILURE MODES (EMBEDDED CAN)

3. FOUNDATION STRUCTURAL HEALTH MONITORING

A novel sensing solution is proposed to monitor the state of large scale multi-MW wind turbine foundations. The system has been designed for 'embedded can' style foundations. The only data currently gathered on the tower movement is based upon accelerometer readings from the nacelle. This data does not give specific details on the foundation. It is unknown how widespread the problems are due a lack of published data relating to wind turbine foundations. As existing embedded can foundations will be in operation for the next 20 – 25 years a suitable monitoring system is desirable. The machines involved in the study were Vestas V80 2.0MW [9] turbines constructed in the last 10 years. During a site visit eight different turbines were inspected. The turbines showed varying degrees of movement. A further turbine was inspected which had undergone remedial work. Figure 4 displays the general layout of a turbine on site.

Figure 4: EMBEDDED CAN, TOWER AND FOUNDATION

The top section of the foundation is completely buried under back fill. The embedded can sits around 30mm above the top of the pedestal and is joined internally to the lower tower section. Due to this construction technique, any movement of the can results in an equivalent movement of the tower and nacelle structure above.

4. EMBEDDED CAN FAILURE MODES

The failure of the embedded can is complex and has several different possible failure modes which may act as one or together over time to accelerate the failure of the foundation. The general layout of an embedded can foundation from the site in question is shown in Figure 5.

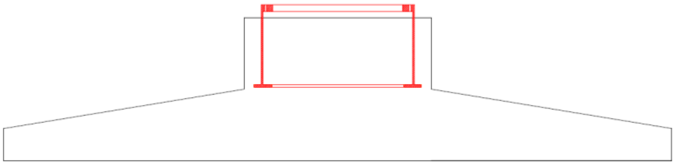


Figure 5: EMBEDDED CAN ELEVATION

The steel can is highlighted and has a diameter of 4m. The foundation has a total diameter of 15m at its base. During construction the steel can is sited and concrete is then poured around to complete the upper part of the foundation. Failure of each foundation is not identical and some may fail at varying rates, as was witnessed during the site visit. The general order of events is listed below:

1. Small movements of the tower are possible due to the low level of friction between the painted can and the concrete. As the tower moves during operation the green plasticized waterproof membrane eventually cracks. Cracking occurs principally around the area between the pedestal and the penetrating steel can. This is shown in Figure 6.

Figure 6: WATERPROOF MEMBRANE CRACKING

There was no evidence that cracking was only occurring in a uniform manner. Some turbines had only small single cracks whereas others have cracks extending to around 2m around the circumference of the foundation/tower connection. This is illustrated in Figure 7.

Figure 7: WATERPROOFING DETERIORATION

2. With the waterproof membrane cracked, water is able to penetrate the foundation, migrating down the gap between the steel can and the concrete. Water migrates between pores within the concrete as well as finding pathways along construction joints. However, with the waterproofing breached much greater volumes of water can penetrate the entire way around the foundation even if there is only cracking at one location. During the site visit it was noted that the water ingress was compounded by ponding on several pedestals and also the constant flow of water running down from the tower during precipitation.

3. The presence of water at the base of the embedded can coupled with the continual movement of the tower creates an environment where erosion begins to take place. The force of the tower movement results in concrete being eroded. The eroded concrete particles mix with the water to create a paste.

4. Evidence of internal foundation erosion is visible at the surface in the form of cementitious deposits being pumped through the cracks at the top of the foundation pedestal (Figure 8). Larger particles that become dislodged such as aggregate are broken up inside the foundation.

5. Voids are created where material is eroded. The presence of voids has been confirmed through the use of remote cameras inserted into the foundation through small boreholes. Video evidence, on this specific foundation, shows the steel can moving in the vertical direction and water being transported around it. Figure 9 illustrates the ingress and location of voids.

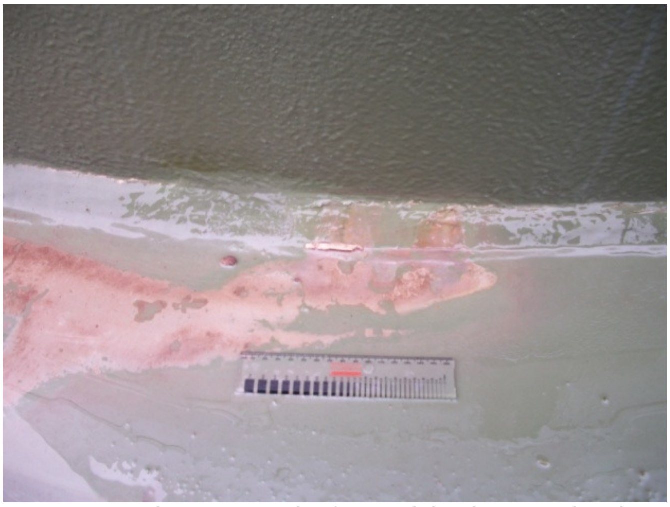


Figure 8: CEMENTITIOUS DEPOSITS EMERGING FROM BASE

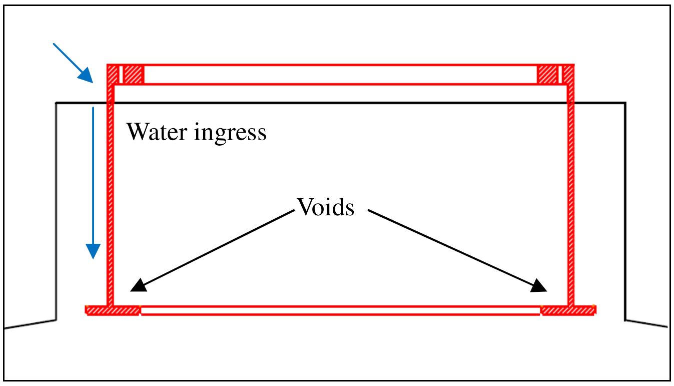


Figure 9: FAILURE MECHANISMS

6. As the depth and width of the void increases the steel can is able to move more in the vertical direction as well as to a smaller extent in the horizontal direction. Erosion is possible both beneath and on the upper side of the flanges.

7. As the steel can movement increases, increased erosion and the magnitude of movement occurs. The amount of material being released from the foundation at the surface is different in each individual case and whilst can be used to suggest a problem is not enough to determine the scale or nature of the failure mode.

8. Eventually the movement reaches a level where remedial action is required. At this particular wind farm it was decided to pump grout into the void in an effort to stabilize the steel can. It is not known for how long this solution will be effective. The turbines which had undergone remedial work were not showing any signs of movement after 18 months.

The pattern of failure has been noted in a number of turbines on several sites with some turbines showing failure early in their operational life and others taking a longer time to develop symptoms. The failures witnessed on site represent a specific wind farm.

5. FOUNDATION MONITORING

Current monitoring for the wind turbines in the study involves a technician visiting each turbine on a regular basis to record visible movement. Inspections are increased when there is a significant change in the magnitude of vertical movement. This method of inspection is time consuming and costly as well as being unavailable for extended periods during winter conditions. The typical measurement approach is illustrated in Figure 10 and incorporates a sight and rule which is magnetically attached to the turbine tower. The technician on site calls for the operating station to request the turbine to be temporarily paused. The greatest movement could be seen during shutdown when it is operating at or above its rated wind speed.

Figure 10: MEASURING DISPLACEMENT MANUALLY

Whilst this method has been used successfully there are some key drawbacks which make it ineffective and inefficient including site access difficulties during winter, the lack of ongoing monitoring and the use of staff resource.

This paper proposes an inexpensive monitoring solution that actively monitors the structural integrity of the turbine and reports its status to a remote technical centre or head office. Inspection of the displacement data and trending can enable technical personnel to improve the understanding of failures and allow the development of appropriate techniques to resolve them.

6. DESIGN REQUIREMENTS

The design requirements for the SHM system to diagnose tower displacement for can style foundations are:

1. Accurate sensing with a resolution of +/- 0.1mm

2. Robust under conditions inside the tower. This includes the presence of oils, hydraulic fluids, moisture and varying temperatures.

3. Measurement frequency of 10 Hz to enable suitable detection of tower displacement.

4. Multiple displacement sensors will be placed around the tower to enable complete profiling of the tower.

5. Data processing and aggregation of the individual sensors allowing the development of a simple traffic-light notification system to enable personnel to easily interpret the status of each foundation.

6. The data collected and processed for each foundation will be categorized for the asset operator. An example classification is indicated in Table 1. The categories have been defined by the asset operator and relate to the degree of the movement. It should be noted that on the site in question vertical displacements of up to 18mm have been recorded by engineers. Data from other sites has been difficult to acquire due to the commercial sensitivities involved although it is thought that movements up to 40mm are possible without total foundation failure and wind turbine overturning. The initial 1-2mm accounts for the elastic stretching of the tower under loading.

Table 1. DISPLACEMENT WARNING SYSTEM

Displacement	Warning Light	Action
1 -2 mm	Green	Least concern
3-5mm	Amber	Increased Inspection
>5mm	Red	Inspection/Remediation

SENSING SOLUTIONS

There are numerous types of displacement sensors available. The most common are Infrared, Draw Wire, 3D MEMS and Capacitive displacement.

Infrared Sensor

Off-the-shelf infrared sensor have an integrated position sensitive detector (PSD) and infrared emitting diode (IRED) [10]. A typical view of the sensor is illustrated in Figure 11.

Figure 11: PSD/IRED DISPLACEMENT SENSOR

The sensor functions by sending an infrared signal towards a reflective surface. The signal is then reflected back to the sensor where it is picked up by the receiver. As the displacement between the sensor and the target reflector increases the voltage output of the device reduces.

Draw Wire Sensor

Draw wire sensors (or string potentiometer) could also be used for the SHM application in a wind turbine foundation. Unlike the IRED sensor the draw wire sensor is always connected to both the foundation and the can/tower. As the can displaces the draw wire uncoils as is shown in Figure 12. The electrical output of the device changes with displacement. Draw wire sensors have been used in SHM application successfully including bridge monitoring in China [11] and landslide monitoring in the USA. This type of sensor is one of the most robust due to the lack of any optics which need extra protection in the foundation to prevent them being splashed by residues falling from the nacelle above.

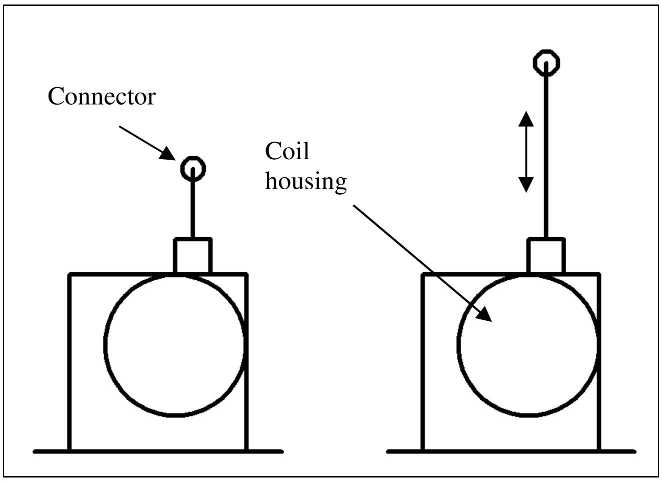


Figure 12: DRAW WIRE SENSOR

3D MEMS

Displacement of the turbine can be measured with low-cost, high-rate wireless 3D micro-electro-mechanical systems (MEMS) accelerometers. The MEMS contain microscopic plates that get stressed by dynamic forces causing a change in the voltage response. They usually use the piezoelectric or capacitive effect to measure acceleration. A typical 3D MEMS sensor is illustrated in Figure 14. Each sensor is capable of measuring the dynamic response of the tower base in three directions. Signal processing techniques are used to convert the accelerations into displacements.

Figure 14: WIRELESS MEMS DISPLACEMENT SENSOR

Capacitive Displacement Sensor

The sensor which has been selected for the foundation is a capacitive displacement sensor. The approach has been demonstrated previously in another SHM application on a road bridge in the form of a wirelessly powered peak displacement sensor [12]. The main difference is the sensor will be used for real time sensing capability rather than only peak displacements. This allows trending functionality with wind speeds which can assist in gaining a greater understanding of the failure factors. The sensor consists of two aluminium tubes which act as capacitor plates. As the steel can moves relative to the static foundation the capacitance of the device changes as the area of overlapping contact area decreases. The sensor is connected to a voltage source and capacitance. As the displacement varies the overlapping area of the capacitance plates changes in a proportional manner. The varying capacitance results to voltages changes which can be digitally captured and processed. The basic layout of the two capacitor tubes is displayed in Figure 13.

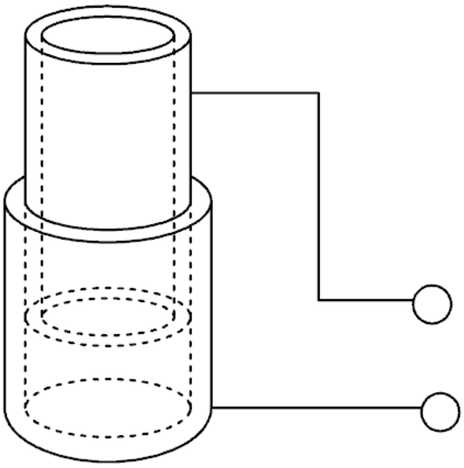


Figure 13: CAPACITOR LAYOUT

The capacitance (C) varies proportionally to the overlap height of the two cylinders (h) as shown in Eqn. (1). It is also proportional to the dielectric constant (K), the air permittivity (ε_0) is the permittivity and inversely proportional to the distance between cylinders (d).

$$C = 2\pi K \varepsilon_0 \frac{rh}{d} \qquad (1)$$

The rate of change of the capacitance in respect to the overlap height is defined by the first derivative (Eqn. 2):

$$\frac{dC}{dh} = 2\pi K \varepsilon_0 \frac{r}{d} \; . \qquad (2)$$

Finally, the captured voltage levels will be correlated with displacement values during the testing phase.

7. CONDITION MONITORING

Data gathered from the chosen sensor system will be gathered, analyzed and displayed in manner suitable for the asset owner. A Bayesian Inference Program will be used to determine the state of the foundation condition.

LabVIEW Bayesian Inference Program

To analyse data from each sensor a Bayesian inference program will be used. Initially, probability density functions (pdf) are created for each foundation condition (Green, Amber and Red). An example is shown in Figure 14 where three pdfs for three component temperature conditions are displayed. For the foundation monitoring system temperature will be replaced with displacement.

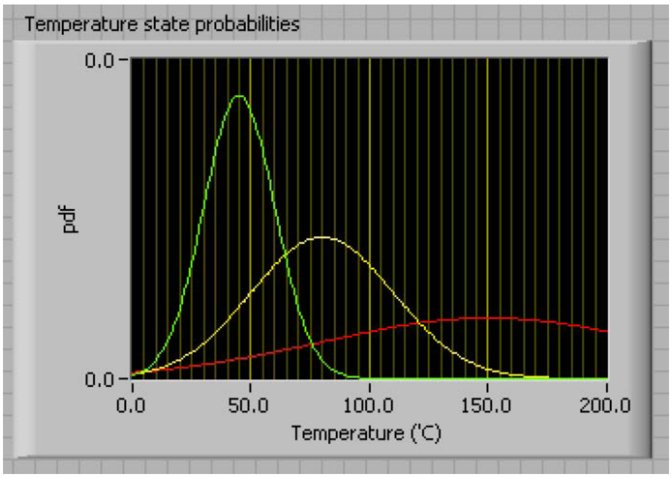
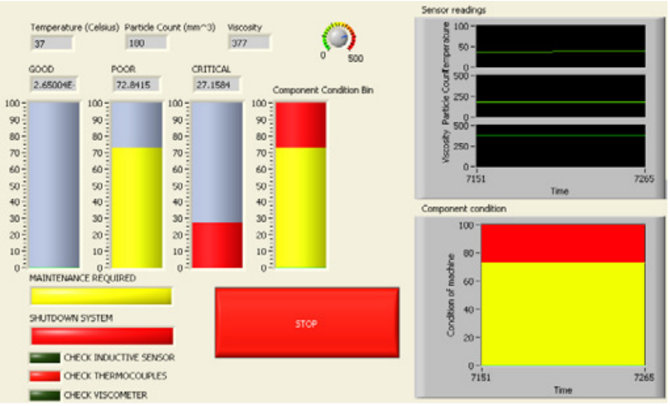


Figure 14: PROBABILITY OF A TEMPERATURE GIVEN COMPONENT CONDITION IS: GOOD, ABNORMAL OR CRITICAL

Once the sensor is active, data is fed into the Bayesian inference program (BIP) where it determines the state condition of the foundation. The output is a simple traffic light system which is easy and quick to interpret by the technician staff monitoring the foundations. Three typical operating modes are displayed in Figure 15 for a wind turbine monitoring. The wind turbine foundation monitoring solution will be simpler as it will only track a single input value. It is envisaged that additional inputs, such as wind speed will be added. It is also quick and easy to change the levels of each of the three conditions, for example to change the critical limit from 5mm displacement to 6mm.



Temperature (Celsius): 37

Particle Count (mm^3): 180

Viscosity: 377

GOOD: 2.65004E-

POOR: 72.8415

CRITICAL: 27.1584

Figure 15: CRITICAL CONDITION

Communication System Architecture

A proposed communications system architecture is shown in Figure 16. Multiple sensors (S) will be deployed on the turbine foundation sampling continuously for displacement and report the measurements to a data aggregator device (A) located in the turbine. The communications between the sensors and the data aggregation device could be either wired or wireless. In order to reduce the installation cost and ease deployment a wireless solution based on the widely used and mature communications standard IEEE 802.15.4 [13] will be adopted. Using this technology devices can operate for more than 3 years with two AAA batteries reporting every 10 seconds [14] making it ideal for SHM applications.

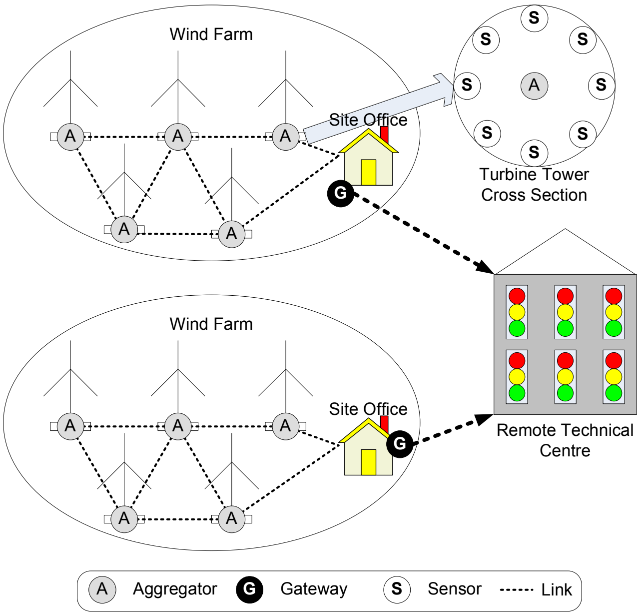


Figure 16: COMMUNICATIONSYSTEM ARCHITECTURE

Aggregator devices are used to combine measurements from the displacement sensors in order to create a displacement profile of the tower as a whole. Also correlation of displacement readings and measurement verification can be achieved at this level (for example elimination of ambiguous readings from sensors placed on the same proximity).

After initial processing, the aggregator devices transmit the combined measurements over the existing SCADA infrastructure to the Remote Technical Centre (RTC) for further processing and classification using a traffic-light system (green, amber, red). The classification and processing will be performed by Bayesian Inference Program and allow the Human Machine Interface (HMI) to display the status of each individual turbine in an easy to understand format. In this scenario the gateway devices (G) shown in Figure 16, are not necessary since communications are handled directly by the existing SCADA infrastructure. Also note that the Bayesian Inference Program will be executed in the Remote Technical Centre.

For wind farms where SCADA infrastructure is restricted or not available due to warranty issues, an autonomous communications solution will be provided. In this scenario, aggregator devices will transmit aggregate measurements to a gateway device (G) which is physically located in the Site Office. The gateway device will have two communication interfaces:

- A wireless interface to communicate with the aggregators. This interface will be based on IEEE 802.15.4 and enlist the aid of aggregators to route measurements from remote locations of the wind farm (i.e. turbines which do not have a direct link to the site office due to limited range).
- An Internet capable interface (i.e. GPRS/HSDPA, WiMAX, Ethernet, ADSL, Cable) for communications with the Remote Technical Centre.

In order to minimize the communications overhead over the Internet link, the Bayesian Inference Program will perform the classification on the gateway device and while the turbine status is green only update notifications will be send back to the Remote Technical Centre for HMI purposes. When the turbine status changes to amber and red, then the gateway will stream measurements back to the RTC along with the normal notifications for further processing, inspection and analysis from technical staff.

If a wind farm consists of a large number of turbines, multiple gateway devices may be deployed increasing data communication bandwidth, reliability and availability.

It is proposed displacement data is trended with real time wind speeds from anemometer point measurements enabling the operator to gain clear indication of relationship between movement and damage. It is expected that displacements are the highest during start up and shut down events and periods of extreme weather conditions. Further work must be undertaken to test and commission the solution and to prove it is robust for this application.

CONCLUSION

Embedded can wind turbine foundations have been displaying signs of failure in the form of vertical displacement. Several inexpensive sensors have been suggested as being suitable for integration in a simple SHM system to continuously monitor real-time displacements in embedded can style wind turbine foundations. The proposed data acquisition and processing architecture allows the asset operator to reduce inspection costs whilst providing greater levels of real time information. Future work will report on field assessments captured from the developed SHM system and provide greater insight to failure modes. This work will also comment on the recommended number of sensors and layout.

NOMENCLATURE

ADSL	Asymmetric Digital Subscriber Line
AE	Acoustic Emission
C	Capacitance
CM	Condition Monitoring
d	Gap distance in sensor
EMI	Electromagnetic Interference
h	Overlap between sensor plates
HMI	Human Machine Interface
G	Gateway Device
GPRS	General Packet Radio Service
IRED	Infrared Emitting Diode
K	Dielectric constant
MEMS	Micro Electrical-Mechanical Sensor
PSD	Position Sensitive Detector
r	Radius
RTC	Remote Technical Centre
SCADA	Supervisory Control and Data Acquisition
SHM	Structural Health Monitoring
WiMAX	Worldwide Interoperability for Microwave Access
WMEP	Wind Energy Management and Evaluation Program
ε_0	Free space permittivity

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(ii) Centre for Advanced Condition Monitoring, University of Strathclyde, Glasgow.

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