Structural Health Monitoring Systems in Difficult Environments—Offshore Wind Turbines

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ABSTRACT

The paper discusses the design and capability of Structural Health Monitoring Systems (SHMS) deployed on Offshore Wind Turbines together with the management of the tasks and risks in the offshore environment. The application of SHMS in difficult environments is a particularly challenging task, where ease of installation, ruggedness and reliability of equipment is essential in providing the key information of the structural integrity of Offshore Wind Turbine Towers. This information is required to evaluate the structural response, status and remaining operational life of the structure. The installation and commissioning of such systems have a significant focus on safety and access to the structures where onsite retrofitting of sensors and instrumentation are carried out in the field. Experience has been gained during the installation and commissioning of over 30 systems that have been deployed in the field in the UK offshore sector over the last two year period.

INTRODUCTION

In April 2010, engineers reported a fundamental flaw in the design of offshore wind turbine foundation structures [1] [2]. The problem affects offshore wind farms across Europe, requiring further investigation into the potential effects on all turbines that have monopile foundations of this design.

It had been confirmed that the grout designed to act as an adhesive between the pile foundation and the transition section of the turbine was failing, and had caused some turbines to slip by more than 25mm. The majority of the, then, 366 UK turbines were built to the same specification and so could potentially develop this fault. Although no safety issues have been identified, as supporting brackets used during construction and left in place have stopped the turbine towers from slipping further, more detailed analysis of the problem was required.

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Strainstall Monitoring were approached by a number of power generation companies and subsequently contracted to carry out testing on a number of wind turbines at seven of the twelve wind farm sites around the UK coastline. Strain gauges, displacement sensors and accelerometers have been installed between the monopile and transition piece to measure displacement and strain, and on the main tower to measure bending, torque and axial load. Two other companies have since appointed Strainstall Monitoring to fit similar monitoring equipment to wind turbine foundation structures of different designs during their construction.

The installation programme started in July of 2010 for the first wind farm and is still on-going as further sensors are added to the initial installations. Monitoring is still on-going on most structures nearly two years after the initial installations. It is hoped by the asset owners and operators that the wind turbines are structurally sound and can be left as they are. The permanent monitoring and alert systems give the operators the necessary structural information to act should the conditions change.

Figure 1. Typical Monopile Wind Turbine (left) and Mini Jacket type Wind Turbine (right).

DESIGN OF A STRUCTURAL HEALTH MONITORING (SHM) SYSTEM

The design of the SHM systems incorporates the reason for monitoring, the type and location of the sensors and the type of monitoring and analysis carried out on the data.

Reasons for Monitoring

The reasons for monitoring define the methodology employed with the design, the type and location of the sensors and the capability of the data acquisition system and data analysis. The majority of the work carried out on the wind turbine structures has been to monitor the response of the Grouted Connections between the Monopile and the Transition piece. The location of sensors were therefore concentrated around this area and installed as a retrofit package to working turbine structures in-situ.

Extensions to the systems were installed to monitor the performance of the replacement elastomeric bearings that were fitted as a modification to the primary structure in the field. These bearings have been installed to spread the load transfer between the Monopile and the Transition Piece. For both types of project mentioned above monitoring systems were fitted as a result of potential problems with the structures found after initial installation. More recently, however, structural health monitoring systems are now being fitted during initial installation of the wind turbine in the field which allow the monitoring of the system from day one throughout the life of the structure.

Locations of Sensors

The location of sensors depends on the reasons and requirements behind the need for monitoring. The location of the sensors is normally defined between the asset owners and operators and Strainstall to determine what is required, for what purpose and how can it be achieved.

Initially the sensors were primarily located at the Grouted Connection between the Monopile and the Transition Piece together with some sensors at a higher location at the top of the transition piece to monitor the reaction of the Transition Piece to the loads applied to it from the Turbine Tower, Generator and Blade assemblies.

Later SHM systems also included instrumentation on the Monopile itself or on the alternative design mini jacket structure where the sensors and cabling were installed at the onshore construction site before offshore installation.

Type of Monitoring and Data Analysis

Using arrays of strain gauges installed at particular positions on the Wind Turbine the stresses experienced by the structure can be monitored and assessed. These strain gauge arrays are used to assess the overall response of the structure in terms of measurement of axial, bending and torsional stresses. They can also be used to investigate the applied stresses to particular details of the design such as the stopper plate brackets. These are the brackets, welded to the Transition Piece, that have prevented the Transition Pieces from slipping any further in some cases as they have come into contact with the Monopile. It is the stresses within these plates that are of particular interest to the asset owners and operators. At these locations the recorded data can be used to provide fatigue life estimates. Additionally Strainstall have instrumented and calibrated a selection of the retro fitted elastomeric bearings with strain gauge based systems to convert the bearings into loadcells.

Fatigue life monitoring of the Wind Turbine structures has been carried out in two ways; firstly by analysing data from installed strain gauges at likely fatigue locations a rainflow counting algorithm can be used to generate stress cycles. S-N curves from fatigue design and assessment references incorporating Minor's Law [3] can then be used to calculate damage and estimated fatigue life. Secondly, using the Strainstall Crackfirst™ technology [4][5], which is a fatigue 'pre-crack' sensor integrated into the monitoring system, accurate predictions of cumulative damage on welded steel structures can be made.

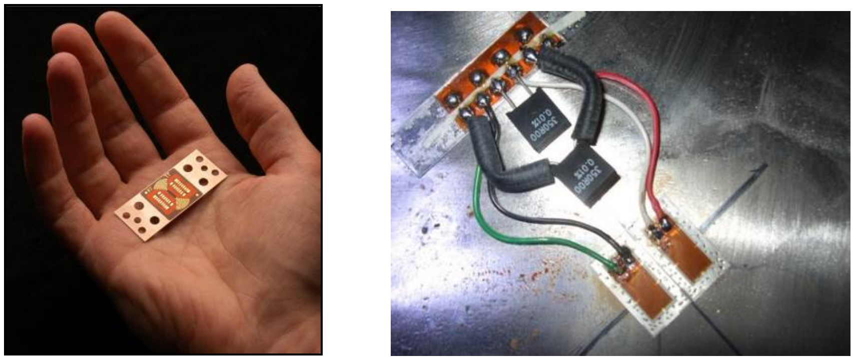

Figure 2. Crackfirst™ Fatigue Sensor (left) and typical Strain Gauge installation (right).

In order to determine the overall vibration and movement of the structure a combination of sensors are used to measure the vibration and sway of the structure together with the relative movement of the transition piece and Monopile at the Grouted Connection.

SHM SYSTEM COMPONENTS

The Structural Health Monitoring System for Wind Turbine monitoring incorporates the following.

Sensors

The types of sensors used with the SHM system for Offshore Wind Turbines are mainly strain gauges, displacement sensors and accelerometers, in addition inclinometers, load cells, wind speed and direction and wave height sensors have been included in the sensor array. The strain gauges installed have been used to measure axial, bending and torsional strains and the gauge installation has included single, Tee and 3 element rosette formats. Due to the conditions the installation has been carried out using micro-spot weldable type strain gauges to minimise any problems due to the environmental conditions during the installation process, these strain gauges are fully waterproofed and where necessary mechanically protected. The strain gauges were made up to be of a full Wheatstone bridge output locally to the strain gauge to minimise any noise pickup and temperature sensors were installed to provide any temperature correction necessary.

Displacement Transducers are used to monitor the relative movement in the vertical and horizontal (radial and torsional) directions over a period of time between the transition piece and the monopile, these devices are of a waterproof type and have to be fitted offshore after the transition piece has been installed.

Accelerometers are used to monitor the sway of the structure and are installed at the top of the transition piece; these devices are used to monitor the swaying of the tower and any change in natural frequency of the structure which could indicate a change in the foundation condition. The accelerometers are installed offshore after the transition piece has been installed to minimise any damage to the sensor and cabling during the installation operations. Some of the systems have also included inclinometers as part of the sensor array to monitor the angle of the Turbine tower structure.

Signal Conditioning

Local signal conditioning for the sensors is provided as close to the sensor location as possible to minimise any noise pickup, provide low pass filtering and isolation. The signal conditioning provides a high level signal output of either ±10V or 4-20mA into the Data Acquisition equipment. The sensors are individually fused to prevent whole system failure.

Figure 3. Data Acquisition Unit (left) and Commissioning System (right).

Data Acquisition

The data acquisition system consisted of a number of 16 bit resolution Analogue to Digital Convertor cards and a compact industrial PC. The data capture rate is typically between 10 and 50 samples per second dependent upon the required frequency content of the signals; additional filtering may be employed. The data is split up into 10 minute period sections; this allows better data transfer to the remote server rather than trying to transfer large data files. The system has a UPS backup for soft shut down and start-up of the monitoring equipment. The system is capable of triggering to and from other equipment therefore alarms status transmission is possible. Where no network is available then GPS clocks have been utilised, GSM modems have been used to control the systems and large quantities of data is transferred using hot swap hard drives that are collected periodically.

Data Recording and Transfer

The data recording and data transfer is dependent upon the status of the Wind Turbine structure and the communications available. The original retrofit systems have been fitted to the structures after the Wind Turbine had been commissioned therefore the ability to transfer data was only dependent upon the communications available. Some systems were originally configured for temporary operation and then converted to a permanent monitoring system. In the case of the SHM systems being fitted as the field was being installed Strainstall have had to provide temporary monitoring systems, and then converted to permanent monitoring systems when the Wind Turbines have been commissioned.

Ideally the data is recorded locally and transferred via broadband connection to a dedicated server for processing with the capability of secure FTP sites for client access.

Data Analysis and Reporting

The data is analysed depending upon the type of sensor and the clients requirements. For example the strain gauges are compensated for any temperature change, principal or orthogonal stresses are calculated and if fatigue life calculations are required the strain gauge signal is run through a fatigue rainflow cycle counting algorithm to extract the completed stress cycles and to calculate the damage through using Minor's Law. For the accelerometer data the acceleration trends are provided together with a frequency analysis using Fast Fourier Transforms (FFT) to present amplitude and power spectrums of the recorded data for normal and alarm conditions.

Data is provided to the client in various ways; these include summary reports of all parameters and events at an agreed period. Alarm events are also sent by SMS or email, raw and processed data is either sent in disc form or access to the data is provided via a dedicated server.

DIFFICULT AND CHALLENGING ENVIRONMENTS

These SHM systems have to be installed and commissioned in tough, hazardous environments. A comprehensive project study is carried out in the pre-planning of designing, installing and commissioning the SHM systems on Wind Turbines. This includes taking into account the Environment, Safety, Access and Training required. It is essential that the design of the system allows the onsite installation and commissioning to be carried out as smoothly as possible.

The environment that the SHM systems have to be installed and commissioned in is a difficult and hazardous one, each turbine is subject to potential extremes of wind, wave and temperature parameters which can change quickly. The potential operations have to bear this is mind to minimise any excessive work procedures and plan tasks to be as easy as possible.

Figure 4. External access from workboat (left) and awkward installation conditions (right).

Safety is paramount when working on these structures. There are many hazards around when working on or accessing these structures. The Turbines are remote in location and have to accessed by work boat, the transfer from the boat to the turbine tower can be difficult and there are vertical ladders to climb both externally and internally to gain access to the necessary parts of the structure. The design of the system has to take into account the transfer of personnel and equipment to and from the worksite and to and from the task location.

Access to the Wind Turbine structure is usually by small support boats that transport the personnel and equipment to the site. Access onto the turbine tower is by vertical ladder navigated from the support boat, internal access is provided by a hatch at the top of the transition piece. Access to the internal structure is by internal vertical ladder. It should be noted that below the air tight platform the area is deemed as a confined space area and appropriate safety equipment and training is required.

Significant training is required to be undertaken by all personnel that are involved in the installation and commissioning of the SHM systems on the Wind Turbine structures. As well as being fit and healthy each engineer and technician requires the following training and experience, offshore survival training and medical, confined space training, turbine climbing training. In addition, all our personnel involved in the installation and commissioning tasks are fully first aid trained and have UK recognised site safety training certification.

CONCLUSIONS

This paper discussed the design of the system and the considerations necessary to successfully install commission and operate a SHM system located on Wind Turbine structures to provide the client with the information required in a timely manner while taking into account the difficulties of the operational tasks necessary to carry out that aim.

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