IT Supported Maintenance, Inspection and Repair of Offshore Floating Windmill Farms

Philippe Renard, Bureau Veritas, Paris/France, philippe.renard@bureauveritas.com

Abstract

We are dealing here with the development of a Decision support system for the online maintenance of an offshore floating windmills farm. This system is expected to be the backbone of the future Condition Monitoring Centres, which will remotely monitor the farms. The automated Decision making module will take into account the specificities of such a farm, in particular the fact that it consists of many identical units. The use cases are investigated and the logics are explained with the necessary level of abstraction and generality, to accommodate future technological evolutions of offshore windmill sensors, NDT measurements and blade repairs.

1. Introduction

This paper uses the results of the ongoing Eurogia+ project named "HLC-AIMS": Eurogia+ is an Eureka "cluster", specialized in the promotion of energy oriented projects. This project deals with an "Hull Life Cycle - Asset Integrity Management System" of offshore floating windmills farms. It was created to develop a methodology and an integrated computer package for the monitoring such farms, which may consist of up to 100 offshore floating windmills (hereafter also referred to as "units") located at sea and normally far away enough not to be seen from the shore. Beyond the required modules for processing all relevant technical data, the ultimate purpose is to build a Decision making interface, advising the farm operator.

This system aims at replacing the real floating object, which is difficult to access at sea, by a virtual representation, for all maintenance, inspection and repair purposes. Seen in that way, applicative tools are ready to supply any requested "animation" of the data kept available in the central database.

It makes sense that off-shore windmills will have significantly more damages from structural causes than on-shore windmills; therefore we have concentrated our effort on structural monitoring.

The anchoring system is part of the project, and some people even think that it is a critical sub-system. It influences the motion of the unit in the waves and therefore the vibrations of the column. Anchoring gives shocks to the structure when it has reached its larger extension. Anchoring is clearly a factor in the RBI analysis. The monitoring of chains in-service is difficult and supporting equipment should be made ready for renewing of chains on site.

This is not a floating windmill design project: as a joke, we could say that we just need a "piece of wood with a fan on the top" as a demonstrator, and take margins regarding stability and wave height. Of course we will try to get closer to an operational design, which was optimized, to be sure that we keep the right order of magnitude for the parameters we are interested in. We will simulate some typical use cases, using records of past experimental data to emulate a floating platform at sea.

2. Condition Monitoring Centre

2.1 Operating schema

The system is designed to support the activity of a Condition Monitoring Centre (CMC), an office for qualified operators, equipped with computers running the system developed in the project. We may imagine the CMC located in high tech areas, far away from floating offshore windmill farms. When an alarm pops up on a computer screen, the CMC operators will call the local Service Centre, which is located on the shore close to the farm, who will send operators to the farm, by boat probably.
Orders are always associated with a feed-back confirmation that the order was executed. Feed-back confirmations will be anyway taken care of in the applicative software or in the workflow. They will be two levels of feed-back: the remote CMC sends alarms to the Service Centre, and receives feed-back from the Service Centre, and the local Service Centre gives orders to the farm personnel, and then receives feed-back from the farm personnel.

Commands to the offshore windmills will be fed back to the farm. We could think of commanding ballasting as a function of the sea state, or changing blade inclination when the offshore windmill tilts under the environmental forces.

2.2 Use cases for Condition Monitoring Centre

2.2.1 Influence of parameters on decision making modules

- In the Rules check module, when steel thickness is smaller, the steel goes from "good" to "substantial corrosion" and finally to "to be repaired", leading to decisions appropriate to each case.
- In the RBI module, the Probability of failure Pf(t) is associated to a given Life duration of the structure Lf: the shorter Lf, the higher Pf(t). If we observe higher stress at a given hotspot, the life duration becomes lower for the structure, therefore the probability of failure Pf(t) is higher and we need shorter inspection intervals to get back to the same level of risk.
- In the FEM module, if steel thickness becomes smaller, the same load is applied on a reduced steel section, therefore we get an higher stress at the hotspot.

2.2.2 Functioning of use cases

- As a typical illustration of how the Decision making module works, let's track the chain of events that occur within the system, when we observe that the stress variation measured by a sensor on an unit, is higher than calculated at the design phase.

As we have a higher stress variation at the gauge location, the FEM module will show a higher stress variation at the hot spot point. Then, combination of higher stress variation level at the hot spot point and original sea waves scatter diagram, provides a shortened expected Life duration (Lf) of the structure. This modifies the RBI analysis, because Pf(t) becomes higher, whence we finally need shorter inspection intervals.
FEM and RBI modules then feed the Decision making module. The Decision making module will require either to reduce the inspection intervals, or to reinforce the structure in order to bring the stress variation back to initially calculated values. This can be obtained by some sort of iteration with the FEM module.

- In following use cases, that we do not detail here, the Decision making module will also take the appropriate decisions:
  - If the measured sea states were higher that those used for the initial calculations, which means that the observed scatter diagram, viz. the matrix of sea states \((H_s, T_s)\), shows higher values than the scatter diagram used in the design phase.
  - If a measured UTM shows a reduction of steel thickness.
  - If a damage is recorded on one unit.
  - If the observed frequency of the structure is closer to resonance than in design conditions.
  - If more vibration cycles were observed so that fatigue calculation needs to be re-run with more cycles.
  - If the observed vibration had a higher amplitude, so that we need to re-run both F.E.M and fatigue calculation.

3. Condition Monitoring Centre software platform schema

3.1 Central database (WCM format)

We have derived from the existing OpenHCM format used for ships and ships-like offshore objects, an exchange format called WCM and dedicated to offshore windmills. This is not that we expect many exchanges through this standard for floating windmills, but it is better to start from a standard which was developed over several years of discussion and which has been continuously updated since its first publication. WCM should represent the unit geometry and objective measurements.

We model the segments, i.e. the large hollow cylinders of steel which constitute a windmill column. One segment is significant in the real world because it is transportable by route. It is made out of several ringshells of homogeneous thickness, which are also represented in the model. We do not refine the model below the ringshell level, because we do not expect a lot of corrosion and we can consider the corrosion as homogeneous in a ringshell.

The format includes very few details for the blades. We define a blade section, typically, every 5 m along the blade. In the blade, all is optional, because we may not get much blade data, which could be deemed confidential.
3.2 General data flow schema

Data from the measurements module (e.g. stress gauges, ultrasonic thickness measurements UTM) and WCM databases, feed the FEM, RBI and Rules assessment modules, which in turn feed the Decision making module. In a few cases, the Decision making module is informed directly, thus bypassing the FEM, RBI and Rules assessment modules.

![Fig. 3: Simplified General Architecture schema](image)

4. Measurements on windmills

4.1 Real time measurements

We can expect that all sensors permanently installed on the windmills will send an enormous amount of data, in quasi real time, to the CMC. These data should be processed separately from the data stored into WCM, which are to be exchanged between the actors of the process.

To reduce the volume of these data, we may completely instrument a few windmills and very partially instrument the others. A correlation algorithm would enable generation of operational alerts from the very partially instrumented windmills.

The goal is to get alerts, and then know what to do when there is an alert. We are speaking here of several hours for intervention delays: in case of high stress, meaning storm, we will not be able anyway to go on board for intervention anyway.

4.2 Instrumentation of the windmill

- Generally speaking, permanent sensors will detect damage location and damage type, while, later on, NDT techniques will be used for verification.

  We will locate the hotspots, in order to install the stress sensors at the hotspots only, which will reduce both the number of sensors and the volume of measurement dataflow.

- Existing sensor technologies applicable to offshore windmills need additional research for appropriate use on board windmills, and especially on blades. Following sensors were considered as usable for the role of permanent sensors on offshore floating windmills:
Vibration analysis (accelerometer or Laser Doppler vibrometer),
- Strains (extensiometric gauges, fibre optics, strain memory alloys),
- Video supervision,
- Water pressure captors (inside tanks),
- Impressed Current Cathodic Protection (ICCP) for corrosion monitoring (parts in seawater).

- Vibration detection is relevant, due to dephasing between wind and hydro-dynamic forces and different wave directions. One complete blades axis revolution lasts about 3 s, in which there are 3 passings of a blade against the column. Measuring vibrations is useful to analyse the observed problems (e.g. correlate the components breakdowns and the vibration levels) or in case of transformation of the structure. The evolution of the natural frequency during the life of the structure is indeed not well known. The structural natural frequency could be higher or lower than the frequency of the waves which is, for instance, about 0.42 Hz in the North Sea.

![Fig. 4: Offshore windmills frequencies](image)

- Regarding stress measurement technology, we can imagine using long-range extensiometric gauges (like sometimes used on ships' decks), fitted inside the windmill unit (to keep them protected from the wind and the sea).

- Nowadays, for offshore structures, there is usually no coating under the sea level, but ICCP protection instead. This should normally be also the case of floating windmills. ICCP monitoring will be part of real time monitoring, because the logics related to imposed current intensity, voltage and hull potential are well known.

### 4.3 NDT measurements

NDT available technologies applicable to offshore windmills are:

- Visual inspection,
- Ultrasonic inspection,
- Acoustic wavefield imaging (AWI, i.e. exciting the structure with acoustic waves and recording the disturbances caused by the wavefield at the surface of the structure),
- Acoustic emission,
- Eddy current,
- Tapometry (excitation of the structure with a periodically hitting hammer and measurement of the output of an accelerometer located on the structure),
- Infrared thermography (illumination of the structure and recording the infra-red radiation emitted by the structure),
- Shearography (comparison of the material surface before and after loading, using interferometry).
Not much corrosion is expected on offshore windmills. We could have fatigue corrosion at the column bottom, but, as it is in the air, wastage is expected to be very little. Cracks detection is more relevant here and the best detection tool for cracks is eddy current.

For blade inspection, we can use a carriage (like those used for window cleaning), or a caterpillar appliance held against the blade by vacuum or magnetic devices.

4.4 Environmental conditions

By contrast with ships, the offshore windmill will always stay at the same location at sea, therefore it will be possible to calculate a normative loading for this area and to update life duration prediction when we have the observed sea states. We will have the history of local sea states recorded by an oceanographic buoy, close to the windmills farm, and we may suppose that we will have the same sea conditions in the future for prediction calculations purposes.

5. Decision making at windmill level

5.1 Finite element model calculations (FEM)

The Finite Element Model (FEM) tool is expected to be useful as a diagnostic tool, to analyse unexpected stress or fatigue levels or to check the effect of structural reinforcements on the unit. We need a parametric FEM model to take care of thickness reduction from wastage and decision making loops in the system when trying to specify reinforcements: as there will be one single windmill model for the whole windmills farm, it will always be possible to define the structure in a parametric way. As shown in Fig. 5, we extract first the data out of the WCM file, in order to define the structure in a parametric way. Then we generate the FEM file, which is an Ansys file in the prototype module.

5.2 Risk Based inspection

5.2.1 Principles

The RBI analysis tells "what, when and how to inspect" for the individual unit: the main tool for decision making at the unit level is the RBI module.

In this project, we minimize the total operating cost of the unit, and calculate its optimum probability of failure.
5.2.2 Workflow description

- The values at unit level and at Component level are noted hereafter with different fonts.

- The probability of failure of the unit $P_f$ is always kept lower than the Risk Acceptance Criteria for the unit, which either reflects the operator's attitude towards the risk or is imposed by normative limitations. The Risk Acceptance Criteria is usually expressed as a probability of failure per year (e.g. $10^{-3}$ failures/year).

- Given an unit with a probability of failure $P_f$, we can allocate $P_f$ down to all individual components of the unit, for instance to the blades and nacelle, the column and floats. Let's say that a given component is thus allocated the maximum probability of failure $P_f$.

We draw, using formulas available in the literature, the probability of failure $P_f(t)$ of a selected hotspot in this component as a function of time. After each inspection at time $T_i$, $P_f(t)$ is supposed to come back to 0.

![Image](image.png)

**Fig. 6:** $P_f(t)$ at component level

- For each component, we can draw the graphs of all possible scenarios $S_i$ of defects, showing detection/non-detection, survival/failure branches. Knowing $P_f(t)$, we can calculate the expected cost of maintenance of the component $C_m[P_f(t)]$, which is the sum of the cost of repair, inspection and monitoring:

$$C_m[P_f(t)] = \sum_i \text{Cost}(S_i) \cdot \text{Prob}(S_i)$$

- For each component, we can calculate the cost of failure of the component $C_f$, as the sum of the costs of failure related to personnel, environment and assets, corresponding to all possible scenarios consecutive to the failure of the component.

- We can propagate, upwards in the schema below, the failures from the lowest levels of the unit to the highest levels of the hierarchical expansion schema, keeping only into account the chains of events that will eventually lead to the failure (collapse) of the unit. Collapse of the unit can result from breaking of anchoring lines, floater ties, blades, etc. One may think of the famous video widely circulated through Internet, where a windmill blade breaks down in high winds, quickly causing the complete collapse of the column.

Starting from $P_f(t)$, $C_m[P_f(t)]$ and $C_f$ of all components and using the "Hierarchical expansion schema", we obtain the probability of failure $P_f(t)$, the cost of maintenance $C_m$ and the cost of failure $C_f$ of the unit.
For each unit Pf, we can run the above steps and draw the expected costs (viz. Cost of maintenance, Cost of failure and the Total cost) versus Pf. The minimum of the Total cost gives the Optimum Pf and the corresponding Cm and Cf for the unit. We can also easily calculate the Criticality of the failure of the unit as Criticality = (Optimum Pf) x Cf.

6. Decision making at farm level

6.1 Goals

The goals of the Decision making module are to minimize the farm exploitation cost over the whole operational life of the structure, and, in the future, to keep the electricity production beyond a certain level, in accordance with the clauses of the contracts covering the sale of the electricity produced by the farm.

In this project, we will estimate the involved costs only roughly. However, the succession of the tools to be used in the process must be correctly defined. Later on, specific parameters will be re-actualized for operating farms, but tools should remain relevant.

We will also answer to questions such as:
• For a given type of interruption of windmill production, when preventive measures are profitable?
• Do we always inspect the same windmills or we create rotations for the choice of inspected windmills instead.
• After a storm, when do we inspect a windmill? Immediately afterwards, 15 days later or when meteorological conditions become favourable again?

The "Decision making" module addresses mostly the farm aspects of this project, which means the "numerous units" issues. We expect to deal with a low risk cost, because there should normally be neither casualty nor pollution.

6.2 "Philosophic" issues

This "Decision making" task contains a lot of "philosophic" issues. The approach of the measurements in this project is rather theoretical and generic, rather than purely technological. Thus, generic parameters, such as sampling, probability of detection of defect (POD), or probability of false detection, will remain applicable when technology of offshore windmill sensors, NDT technologies and blade repairs evolve. We need to distinguish between continuous monitoring (e.g. stress gauges, imposed protective current, movements of unit, position of unit) and inspections where we go and inspect an unit and then find something (e.g. we have seen no crack). There are also processes which can be processed through RBI (e.g. corrosion, fatigue), and those which cannot be processed through RBI (e.g. coating degradation).

After an RBI analysis, there could be either a "local loop" to update one unit only, or a "farm loop" that would update all units in the farm. For instance, the probability of detection (POD) of a defect, which plays a role in "detection/no detection" branches of the graph of scenarios, is influenced by what we know of the whole farm condition.

The continuous update of the system parameters is a major feature of this system which could be qualified as a learning system. The fact that farms are made of numerous identical units, favours the efficient correction of theoretical values by the observed measurements.

On top of the Decision making module, there is always an expert's decision. For instance, the observation of higher stress than expected could induce the expert to have a look at sea conditions (exceptional stormy conditions) or vibration levels (maybe sea frequency is closer to structural frequency than expected).

6.3 Strategic options

Decision making should incorporate some sort of strategic options. This may go from the "discardable windmill" principle to a long term maintenance policy of all units of the farm. Class rules can also be seen as a simple sort of strategy: for instance, Class rules lead to the decision of plate replacement when a certain normative wastage is reached.

As there is no drydocking for offshore windmills, maintenance strategy becomes more significant than for ships. Among well known maintenance strategies, some do not apply to a small (less than 100) number of objects (e.g. MTBF).

6.4 Sampling issue

The main sampling problem can be stated as follows: if we inspect only a sample of windmills, what is the risk of drawing wrong conclusions at the farm level? A possible strategy is to prescribe that after a certain time, all units must be inspected. The rationale would be that, after a while, there is so much uncertainty that we cannot avoid physical inspection. But, if we always monitor the same units, the quality of follow-up is improved.
The most challenging issue is not, from the observed "number of default observations / size of the sample" (p/N) of the sample, to extrapolate to the average p/N for the population, with a certain degree of confidence, but to tell how this extrapolation influences the RBI process.

Acknowledgements

The author would like to thank the following persons for supplying valuable material used to write this paper:
- Antoine Rouhan, Jean Goyet, Bureau Veritas, Paris/France for WCM format, general system architecture schema and RBI module specification,
- Piet Moerland, Materiaal Metingen Europe, Ridderkerk/Netherland, for measurement and NDT technologies applicable to windmills,
- Arnaud Thiry, Amirouche Amrane, Philippe Rigo, Jean-David Caprace, ANAST ULg, Liège/Belgium, for vibrations and FEM module specification,
- Adrian Constantinescu, DN&T, Liège/Belgium, for windmills condition monitoring system and maintenance strategy,
- Zakoua Guédé, Benoît Bigourdan, Ifremer, Brest/France for demonstrator definition and specification of decision making at farm level.

References

RENARD, P.; ROUHAN, A. (2009), *Asset integrity management system for ships and offshore units hull maintenance*, 8th Int. Conf. Computer Applications and Information Technology in the Maritime Industries (COMPIT), Budapest