Failure and Remaining Useful Life Prediction of Wind Turbine Gearboxes

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Abstract

The purpose of this project is to predict wind turbine gearbox incipient faults using a combination of condition monitoring data. It is expected to contribute in developing a robust framework for wind turbine gearbox component incipient failure prediction and remaining useful life estimation. It further proposes a solution on how to overcome the challenges of expert knowledge based systems using AI techniques. Wind turbine operation and maintenance decision making confidence can be therefore increased.

1. Introduction

A large proportion of the total cost of energy from wind in large wind farms is composed of operation and maintenance (O&M) costs, which can be reduced if incipient machinery faults are successfully detected before they become catastrophic failures. For that reason, a combination of preventive and corrective maintenance strategies is implemented in wind industry (Sinha & Steel, 2015). Preventive maintenance can be performed through SCADA (Supervisory Control and Data Acquisition) systems and Condition Monitoring Systems (CMS). In both onshore and offshore wind, the wind turbine downtime is dominated by gearbox failures (Wilkinson et al., 2010), (Carroll, McDonald, & McMillan, 2016). It is thus vital to successfully monitor this component. Furthermore, as the installed wind capacity grows, the volume of condition monitoring data increases. The variable loading conditions of wind turbines and the nonlinear relationships between the parameters render rule-based monitoring impractical. For all aforementioned reasons, manual interpretation of wind turbine data becomes challenging. Therefore, Artificial Intelligence (AI) techniques can aid the decision making process of wind turbine gearbox maintenance.

Based on the problem statement, the objective of this thesis is to answer the following research question and a high level methodology overview is given in Figure 1.

"How can gearbox faults be predicted based on a combination of condition monitoring data before catastrophic failure occurs and how can information from similar wind turbines be used?"

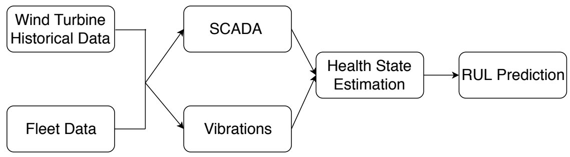


Figure 1. Thesis Flowchart

2. Anomaly Detection Using SCADA data

There is a large amount of SCADA data available, which can be used to give an indication of the turbine condition. These data are the cheapest source for developing condition monitoring systems for wind turbines. The data can be operational, environmental or status codes. Anomaly detection and health assessment of a wind turbine through SCADA can be performed in various ways (Tautz-Weinert & Watson, 2016). One of them is through normal behaviour modeling (Zaher, McArthur, Infield, & Patel, 2009). a measured parameter is modelled empirically based on a training phase and the residual of measured minus modelled signal acts as a clear indicator for a possible fault. An example is shown in Figure 2. SCADA data is available at different time periods progressively before failure from 199 operating wind turbines. All turbines experienced a planet bearing inner race fault. The temperature in the hollow shaft is predicted using neural networks, based on other temperatures, the power and the speed of the turbine. The mean absolute error of predicted temperature increases towards failure. System level health assessment can be easily achieved but gearbox specific component fault detection could be more challenging.

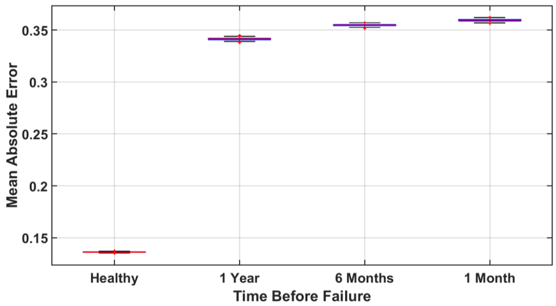
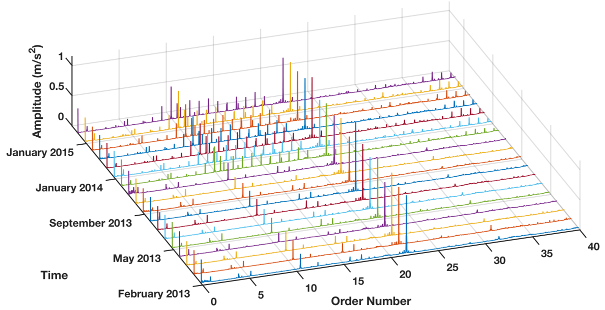
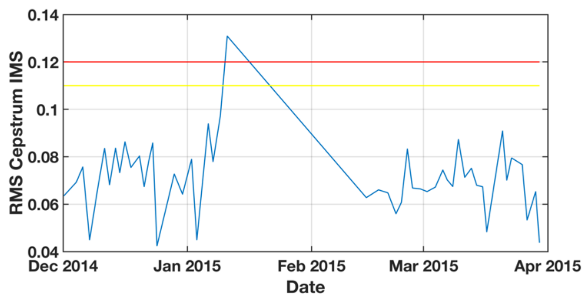


Figure 2. Normal behaviour model mean absolute error when predicting a gearbox hollow shaft temperature.



(a) Order spectra of wind turbine gear before failure



(b) Operator RMS feature and threshold alarms

Figure 3. Case Study of high speed pinion failure. Order spectra building up to failure (3a) and rule based system alarm (3b)

3. VIBRATION SIGNAL ANALYSIS AND CLASSIFICATION

Vibration signals can give a more informed indication of gearbox component failures. Diagnostics of vibrations signals has been widely researched in the literature and different methods regarding wind turbine gearboxes are evaluated and presented in (Sheng, 2012). The proposed methodology utilises various vibration analysis methods in order extract features from the signals of interest. The vibration analysis methods involve transforming the signals into the frequency/order domain or time frequency domain where fault signatures are revealed more clearly. The features extracted based on these fault signatures, are used as inputs in pattern recognition models that can determine the health state of the components (Koukoura, Carroll, & McDonald, 2017). An example is shown in Figure 3a from a real gear tooth crack failure on the high speed shaft pinion. Sidebands around the gear mesh frequencies are an indication of an incipient gear fault. Statistical features are extracted on a narrowband space around the frequencies of interest. Classes are assigned to the signal based on expert judgment and the time before failure. A binary classification is initially attempted, where signals are categorized are ”normal” or ”abnormal”. Results are evaluated based on the robustness, missed detection rate and how earlier faults can be detected compared to rule-based methods which are the current practice. The RMS feature and its thresholds from the operator are shown in Figure 3b. In this case study the change in vibration signals due to the presence of a developing fault is captured by the pattern recognition model, as shown in Table 1, months before before the alarm was activated . Approximately 700 samples are used for training this specific model.

Table 1. Binary classification results

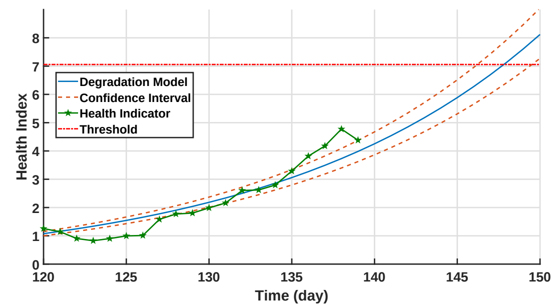
Recall	Precision	F1 Score
96%	93%	94%

Load and temperature play an important role in the the vibration signature of the gearbox components. Therefore, SCADA data information of power level, speed and temperature is incorporated in the vibration classification models. Depending on the sampling regime of vibrations and SCADA, load and environmental parameters can be used directly as input features to the pattern recognition model or some type of correlation technique can be applied.

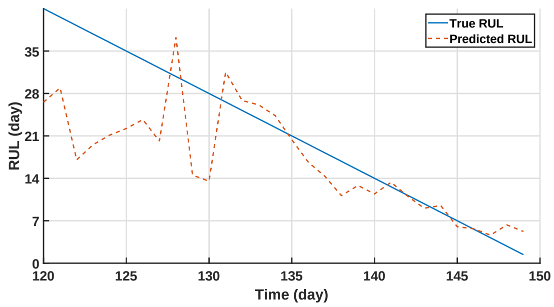
The example presented focuses on fault detection. Since the features extracted are around specific fault frequencies and sensors, fault diagnosis can be achieved. The aim of fault diagnosis is to identify specific faults from the rest of the data (Leahy et al., 2018). Therefore, classification of different faulty components (i.e. gears or bearings) around different stages of the gearbox is to be explored in the thesis through different failure mode case studies.

4. REMAINING USEFUL LIFE ESTIMATION

Once an incipient fault has been detected, fault prognosis is performed. Features extracted from vibrations can be ranked and fused to create a health index (Coble, 2010). Remaining useful life is estimated using degradation models (Saidi, Ali, Bechhoefer, & Benbouzid, 2017). Either measurements or historical run-to-failure data can be utilised for that reason. Parameters are yield to prior Gaussian distributions and are updated when new observations are available. Some preliminary results from a planet bearing remaining useful life



(a) Degradation



(b) RUL

Figure 4. Prognostic results of planet bearing. Health index degradation model (4a) and $\alpha - \lambda$ plot (4b)

estimation are shown in Figure 4, for the bearing degradation stage. An exponential model is used.

5. FLEET BASED FAULT DETECTION

If enough historical data is available, turbine unit specific diagnostics and prognostics can be performed. On the other hand, fleet-based diagnostics and prognostics can provide a robust fault detection framework based on similar wind turbines. Assuming that the majority of wind turbines in the fleet are in normal operating condition, a clustering approach can identify baseline data and detect abnormalities (Lapira, 2012). The normal operation identified from the fleet data is taken as baseline, and is used to train a global fault detection model using data-driven approaches.

6. CONCLUSION

The thesis provides a framework for fault prediction of wind turbine gearbox components, using inputs from various sensors on the wind turbine drivetrain. The features extracted from those sensors are used to train models that determine the health state and the remaining useful life of the components. Fleet based condition monitoring is also explored, since it can significantly improve the decision making process.

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Sofia Koukoura received her degree in Mechanical Engineering at the National Technical University of Athens in 2015. She then joined the University of Strathclyde Wind and Marine Energy Systems Centre for Doctoral Training. Her PhD focuses on diagnostics and prognostics of wind turbine gearboxes using signal processing and machine learning techniques.