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Monitoring Gearbox Using a Wireless Temperature Node Powered by Thermal Energy Harvesting Module

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***Abstract*—Condition monitoring (CM) of gearbox is a crucial activity due to its importance in power transmission for many industrial applications. Monitoring temperature is an effective mean to collect useful information about the healthy conditions of the gearbox. This study investigates the use of a novel wireless temperature node to monitor and diagnose different faults on a gearbox transmission system under different conditions. The wireless temperature node was fabricated with a novel feature that it is supplied by a thermoelectric generator module mounted on the gearbox house to be monitored so that the measurement system avoids the shortage of using a wired power sources or the requirement for recharging or changing batteries. Moreover, the temperatures from lubricating oils and housing are modelled empirically to implement a model based detection. The results show that this monitoring approach allows a number of common faults: tooth breakage, oil shortage, and shaft misalignment to be separated under different loads, which demonstrates the outstanding performance of the proposed system and thus suitable for online and automated condition monitoring.**

Keywords-gearbox; condition monitoring; temperature; fault diagnosis.

I. INTRODUCTION

Maintenance has become increasingly important to the industrial automated manufacturing process. Meanwhile, the investment on maintenance has grown quickly with the increasing the complexity of machine systems. Appropriate use of CM can be applied for detecting faults at an early stage, reduce gear repair and maintenance cost. Therefore, to improve upon the monitoring techniques and analysis tools, there have been constant improvement methods for finding the gear conditions. In which, a wide range of techniques have been applied to diagnose gear faults.

Temperature monitoring is one of the most commonly and extremely known monitoring techniques used in the industry machines. It is widely used for monitoring mechanical and electric machine. It can provide useful information for monitoring the condition of the machine components. Monitoring of gearbox is crucial activity due to its importance in power transmission in different industrial application systems. Any defect in gear lead to machine downtime and resulting in a loss of production [1]. The maintenance cost of the gearbox is very high as compared with the other failure rate components such as electric system and hydraulic system. With the rotating speed and load of different stages of gearbox change from time to time, bringing great challenges to the CM of gearbox [1-3]. Cost performance is another factor that should be taken into account of gearbox condition monitoring. Comprehensive introduction and analyses of condition monitoring methods for different components of gearbox have been published recently [2-4].

The temperature is easily measured and important indicators for the health of many machine components such as gearbox and is often recorded automatically using data acquisition system [5, 6]. An unexpected increase in component temperature may indicate an overload, poor lubrication or possibly ineffective passive or active cooling. Reference [5] used temperature trend analysis to monitor the gearbox's operating conditions. The Auto Associative Kernel Regression (AAKR) method is used to model the normal behaviour of gearbox temperature and give temperature estimates. When the gearbox has an incipient failure, the temperature residual between the AAKR model estimate and real measurement will become significant. With moving window residual statistics, these incipient failures can be detected in a timely way. In [7], a neural network used to construct the normal operating temperature models of gearbox and generator based on SCADA data. When the residual between the model prediction and the measured value becomes very large, a potential fault is identified. Multi-agent methods can be used to combine the CM results of different components. In [8] the authors proposed a method using a Multiple Layer Perception (MLP) to build a temperature model of the gearbox. When the measured temperature value increases and is outside the confidence range of the value, a fault is registered. [9] In this paper, proposed a temperature trend analysis method based on the nonlinear state estimate technique (NSET). At the outset, NSET is used to construct the normal operating model for the wind turbine generator temperature and then at each time step the model is used to predict the generator temperature. The time series of residuals between the real measured temperature and the estimate is smoothed using a moving average window in order to reduce the sensitivity of the method to isolated model errors, thereby improving its robustness. When the generator has a potential fault, the time evolution and the distribution of temperature residuals will be different from that for normal operation.

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Thermoelectric generators (TEGs) are solid state devices, which mean that they have no moving parts, produce no noise and involve no harmful agents. TEGs are the most widely adopted devices for waste heat recovery. The ability to generate electrical power from a temperature difference across a material is due to the Seebeck effect [10-13]. Many applications have been used with TEGs such as structural health monitoring applications [14, 15]. The TEG have been also used for energy harvesting in structural health monitoring areas [16].

Wireless sensor networks (WSN) becomes an adopted method for many applications including complicated tasks. However, the WSN has removed the long communication cables of the measurement system, the wireless sensor node still needs dedicated power line or regular charging-replacing the batteries [13, 17], which induces additional works to field engineers and is a major shortage of using WSN for CM. In recent years, energy harvesting offers an effective solution to this problem due to its inherent advantages, such as low cost and easy deployment. Many kinds of wireless transmission technology have already been used such as ZigBee, Bluetooth and ANT. Bluetooth V4.0 is the most recent version of Bluetooth wireless technology. Bluetooth Low Energy (BLE) has been designed as a low power solution for control and monitoring applications [18].

In this study, a wireless temperature node has been applied to monitor and diagnose different faults on a gearbox transmission system under different conditions. In which, the wireless temperature node was supplied using a wired power sources without needing for charging problems.

II. TEST FACILITY AND MEDHOD

An experimental test rig shown in Figure 1 was employed in this study. The test rig components consist of a 15 kW, 3 phases induction motor as the prime driver, two back-to-back two stage helical gearboxes for coupling the AC motor with a load DC generator using flexible spider rubber couplings. The transmission power of each gearbox is 13 kW with a transmission ratio of 3.678. The first gearbox (GB1) operates as a speed reducer while the other (GB2) is a speed increaser. In this way, the system maintains sufficient speed at the DC to produce an adequate load on the AC motor [19-21].

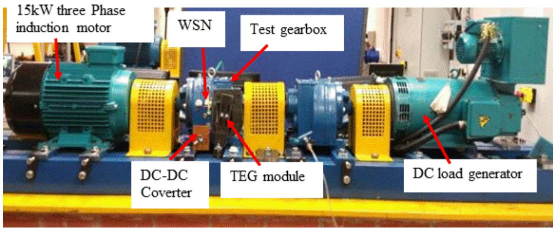

Figure 1. Test rig construction

A. *Wireless Temperature Node*

To measure gearbox temperature, an integrated wireless sensor node named Sensor Tag is employed. As shown in Figure 2, this compact sensor node integrates 10 low-power MEMS sensors and a two core BLE microcontroller CC2650 [22]. Two temperature sensors are available on the node with one for measuring object temperature and the other one for ambient temperature. Another benefit of this module is that its programs are open source, which enables to customize the data acquisition and embed intelligent signal processing algorithms on it.

The sensor Tag is specially designed for low power consumption applications and can be supplied by a coin battery [22]. Here, the coin battery is not used; instead the sensor tag is powered by the energy harvested from waste heat in order to avoid the inconvenience of changing the batteries during the lifetime of the system.

Figure 2. Sensor tag CC2650K

The CC2540 USB evaluation module kit as shown in Figure 3, contains one Bluetooth low energy USB dongle. The dongle can be used to enable Bluetooth low energy on our PC. The CC2540 combines an excellent RF transceiver with an industry- standard enhanced 8051 MCU, in system programmable flash memory and 8KB RAM. It is selected on the USB because it suitable for system where very low power consumption is required. It also very low power sleep modes are available and low cost [23]. It employed to receive data via the Bluetooth low energy from the sensor tag.

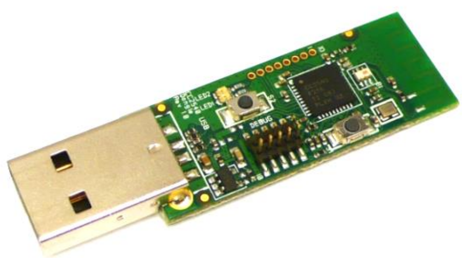

Figure 3. USB module

B. *Thermal Energy Harvesting Generator Design*

The thermal design as shown in Figure 4, which consists of: TEG thermal insulation material, a heat sink, and two pieces of thin aluminium have been chosen, one piece to work as a heat collector for hot side, whereas another one acts as a heat spreader for cold side, due to the large thermal conductivity of aluminium. The design was built by using a commercially available TE module CP85438 [24]. The TEG is sandwiched between two pieces of aluminium. The aluminium plates have been chosen due to the good thermal conductivity of aluminium. Note that, some thermal insulation materials are stuffed between the two pieces of aluminium plates to reduce the heat transmission through the air from hot side to the cold side. A thermal insulating material, (thermal heat sink transfer double side adhesive) which is designed to maintain temperature difference between hot and cold side of TEG, also another insulation material which is designed to surround the TEG module, which has been worked in the thermal design to isolate the heat source from the heat sink because the heat source is close to the heat sink that is reduce the heat transfer capability of the heat sink.

Heat sink plays an important role in the thermal energy harvester to maintain a temperature difference by radiating the heat on the code side of the TEG module efficiently to the surrounding air. Here a medium size heat sink with thermal resistance of 1.5 °C /W has been used.

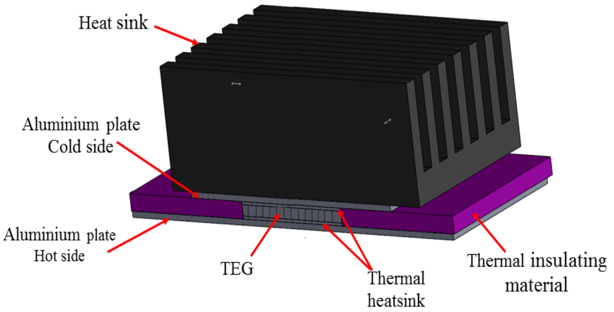

Figure 4. The TEG module

The voltage output of the TEG module are usually very small, with only about several mW to a few hundreds of mW depending on the temperature difference on its two side. Such a small voltage cannot be directly used for either charging or powering the sensor node. Therefore, a DC-DC converter is usually added at its output for boosting the low voltage to a higher one. Here, an integrated DC-DC boost converter LTC3108 [25] has been employed. It can boost an input voltage ranging from 20mV to 500mV to an adjustable one from 2.35V to 5V. Simple in design and low in cost, the circuit can boost the small voltage from the TEG in a convenient way. The output voltage is fixed at 3.3V for directly powering up the sensor node. A super capacitor with a capacity of 0.22 F is employed for storing extra energy harvested. It is used when there is no energy harvesting or if it is not sufficient for the continuous node operation.

C. *Test Precedure*

The test rig was operated at a fixed speed of 1470 rpm, 100% of the rated speed of AC motor, under four incremental load settings: 0%, 30%, 70% and 100% of the full DC load. The aim is to investigate the detection process under constant speed and variable load operations, which are common scenarios in real applications. Each load setting operated for a period of five minutes and was automatically changed to the next step by the PLC controller. In total, for all loads cycle lasted 20 minute and was repeated twice as depicted in Figure 5.

Three different faults have been studied, i.e. tooth breakage, oil level reduction (600ml less than the specification) and 0.13 mm shaft misalignment between the gearbox and the driving motor. The studies faults represent some of the most common faults that occur in mechanical transmission systems. Additionally, the detection of these faults using temperature analysis. Tests performed are to examine the performance of a temperature based fault detection scheme and to investigate the diagnosis capabilities of the temperature analysis.

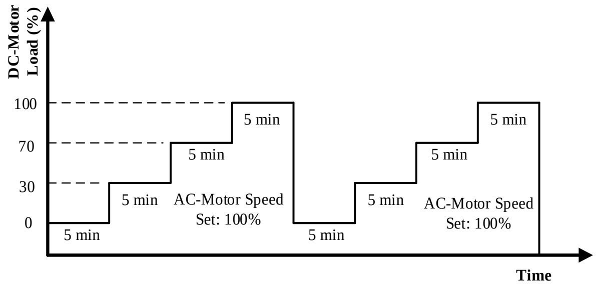

Figure 5. Test cycle

III. RESULT AND DISCUSSION

The experimental works have been performed to detect different gearbox faults, tooth breakage, oil level and shaft misalignment, in which an algorithm model based on data-driven modelling was developed for complementing the dynamic interactions of gearbox transmission temperature. The gearbox was tested under three different defective conditions, in which the temperatures of the oil and surface of gearbox have been measured simultaneously.

A. *Baseline*

Figure 6 shows the oil temperatures of the gearbox measured by temperature sensor and the housing temperature of the gearbox measured using the sensor tag, the surface temperature called housing temperature. From this figure, it can be seen that the oil temperatures of the three cases under normal working conditions vary from 41 ◦C to 46 ◦C. However, housing temperature of the gearbox fluctuates between 33 ◦C and 36 ◦C, due to the effect of fan cooler of the AC-motor, which effect the surface temperature of the gearbox. The condition of tooth breakage has the highest temperature of lubricating oil. However, the condition of shaft misalignment (0.13mm) has the highest temperature of the recorded housing temperature. Furthermore, the condition of oil level reduction (600ml less) has the lowest temperature for both oil and housing temperatures because of less churning losses [26].

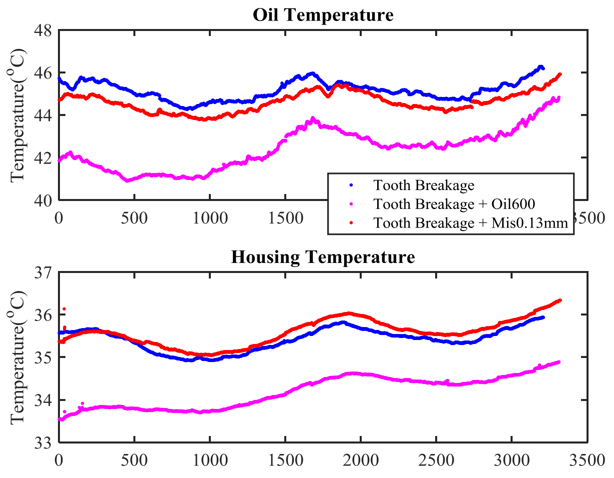

Figure 6. Comparison results of surface temperature and oil temperature of the gearbox with different conditions

Figure 7 shows the relationship of the housing temperature and oil temperature of gearbox at different loads. It can be observed that both temperatures of gearbox under tooth breakage and shaft misalignment at different loads is higher. However, the relationship of the oil and housing temperatures with less oil level show the lowest temperature behaviour. Based on these relationships, an empirical model has been developed based on data-driven modelling for complementing the dynamic interactions of gearbox transmission temperature.

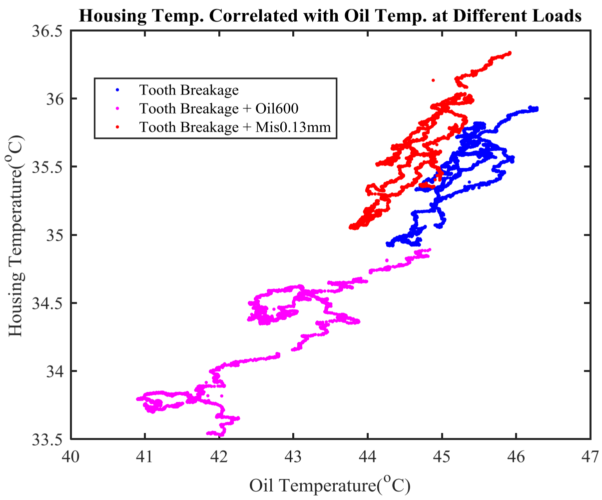

Figure 7. Results of surface temperature and oil temperature at different loads

In this study, a model has been developed based on polynomial fitting of training and predicting temperatures, as illustrated in Figure 8. In implementation, baseline condition was developed within tooth breakage fault to define the limitation regime of proper gearbox working condition. The developed model is mainly based on data-driven modelling, which was used to build models for complementing the interaction dynamics of gearbox transmission temperature.

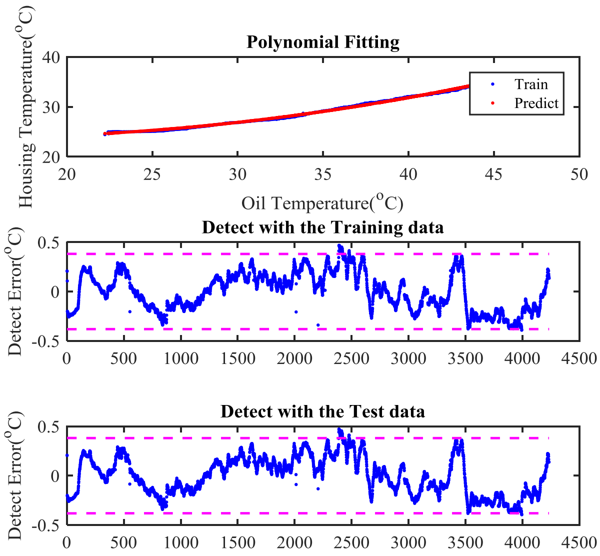

Figure 8. Data drive model based on gearbox temperature

An empirical algorithm model is used to determine the relationship between the gearbox oil and housing temperatures based on a training data set that represents the gear system behaviour. The model would be useful in solving a practical problem with complex periodic signals such as the gearbox faults. The baseline signal has been constructed to define the basis condition for the model.

This model can be used to monitor the abnormality condition of the gearbox. Figure 9 illustrates the transmission paths of the heat to the gearbox housing during gear meshing process, whereas oil and bearing are the main transmission paths of the generated heat to the gearbox housing. The main sources of heat generation are the friction induced between the teeth contact surfaces during the meshing gears and the friction due to oil viscosity. More transmission loads increase the contact friction between the meshing gears, hence the oil temperature increased based on the applied load conditions. Thereby, three different conditions have been simulated under different operating conditions, to confirm the developed model. These faults are mainly related to the transmission paths of heat mesh generation.

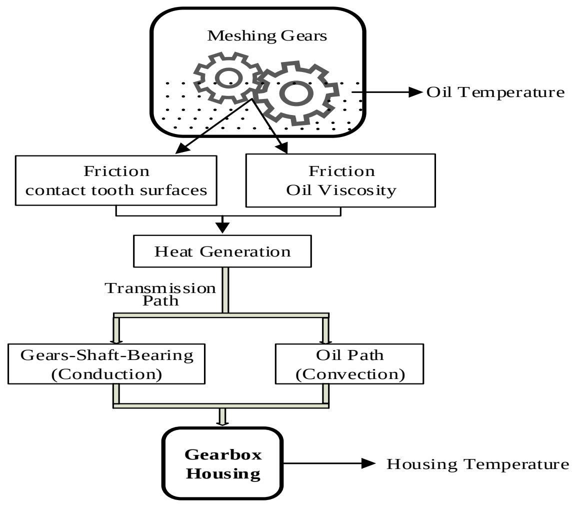

Figure 9. Transmission path of gear mesh temperature

B. Oil Level Reduction

Figure 10 depicts the relationships between the oil temperature and the housing temperature of the gearbox when the oil level was decreased by 600ml. The oil temperature and gearbox housing temperature are generally increased with increasing load. In which, the detection model signal is changed significantly due to the shortage in oil condition. This can confirm that some changes have been changed in the transmission paths of gear mesh temperature, which can be mainly related to the oil transmission path. The detection signal is changed based on the oil shortage and the detect error model is out of baseline range.

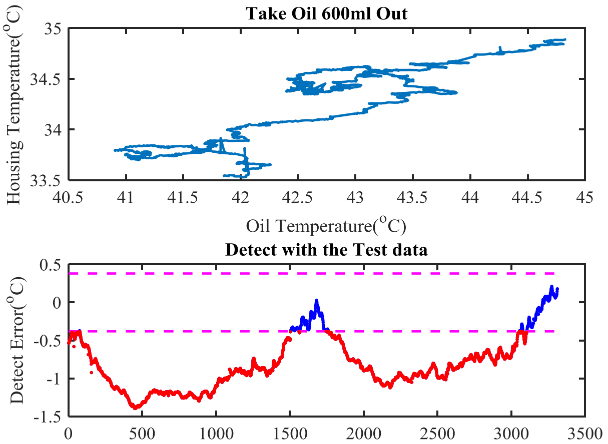

Figure 10. Results of surface temperature at oil level (600ml lees)

C. Shaft Misalignment

Figure 11 illustrates the same relation of the gearbox temperatures under the effect of shaft misalignment at different loads. In which, the conduction path of the gear temperature via the bearing is influenced and more heat is generated that increase the oil and the housing temperatures. The detection model signal is changed due to the shaft misalignment condition and most of the detect signal is out of the limited region.

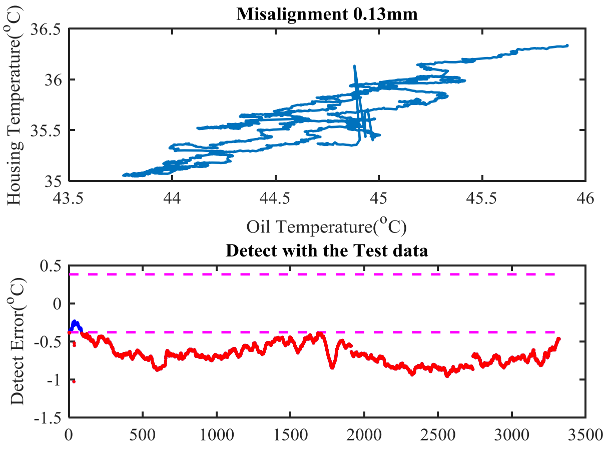

Figure 11. Results of surface temperature at shaft misalignment

IV. Conclusion

Modelling the temperatures measured internally and externally is effective for the detection of abnormal gearbox operations. The model allows an accurate description between the internal heat generations due to gear friction and oil viscous drags, the heat conviction through the oil and the conduction by the shaft-bearing. Therefore, any changes occurring on these aspects can be detect by model based approach. In particular, common deteriorations in gear meshing conditions such as tooth breakage, lubricating performance such as oil shortages and installation of the gearbox such as shaft misalignments have been demonstrated to be detectable using the approach proposed. In addition, the fabricated wireless temperature nodes is reliable and accurate to obtain the temperatures without using any cables and power supply. These unique features together with the outstanding performance of fault detection make it particularly suitable for online and automated condition monitoring.

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