Multi-source Energy Harvesting Powered Acoustic Emission Sensing System for Rotating Machinery Condition Monitoring Applications

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Abstract: This study concerns with the acoustic emissions (AE) monitoring for the applications of rotating machine fault detections. The first prototype wireless AE sensor system with vibrational, thermal and light energy harvesting power supply is presented in this paper. This prototype regularly records the AE signal at 150-250KHz frequency bandwidth and compares with known gear/bearing fault patterns. The data are compressed and transmitted via Zigbee based wireless transceiver to nearby central control unit. The multiple-source energy harvester proposed in this work generates 1.56mW from 0.048g vibration energy and 3.37mW thermoelectric energy when deployed on the 62^{o}C metal surface of a gas compressor. This battery-less wireless AE system achieves power autonomy from environmental energy, realizing a self-powered easy-to-deploy wireless data transmitting based health monitoring solution for wide range of rotating machinery.

1 INTRODUCTION

Rotating machinery such as electric motor, turbine and air compressor are widely equipped in great many industries, such as general manufacturing, power generation, refrigeration and many others. In rotating machinery, gear and bearing are critically important components. They are required to operate with high reliability for extended period of time in harsh environmental conditions. Unexpected Faults (UFs) of the gear and bearing may lead to damages of entire machine. Consequently, these UFs will cause considerable machine repair/replacement cost, and also the associated labour and downtime costs. Therefore, periodic non-destructive testing (NDT) and on-line condition monitoring (OCM) are often used to conduct preventive maintenance (PM) in order to effectively diagnose and prevent further development of faults (Bastianini et al., 2013).

Since early 2000s, the method of Acoustic Emission Monitoring (AEM) has been proposed for PM applications (De Silva, 2010) and (Bohse, 2013). Acoustic Emissions (AE) in rotating machinery are transient elastic waves produced by the interactions of two media of gears/bearings in relative motions. AEM methods "listen" to and process the elastic wave signals and used the interpreted information to diagnose the potential faults in the early stage of surface/subsurface crack formation.

The evolution of wireless sensor networks (WSN) technologies in the last decade provides an unique opportunity for the further development of NDT systems (Grosse and Krüger, 2006). The micro-controller (MCU) and low-power wireless transceiver based WSN module (mote) is substantially less expensive and less power-hungry than the conventional programmable logic controller (PLC) and Modbus serial communication based monitoring system. In addition, the battery powered WSN can be deployed with minimal installation cost. WSN based AEM system has been proposed for infrastructure (bridges and buildings) structural health monitoring applications (Ledeczi et al., 2009) and (Aygün and Gungor, 2011).

However, a bottleneck of WSN development is the limited battery energy. The 0.5 milliwatts ultra-low power WSN system can only achieve 6-month battery lifetime when powered from 1000mAh battery in optimal condition. The task to regularly replace battery can become expensive when the number of WSN motes is large and even impossible when the mote is placed in difficult-to-access locations.

Energy harvesting technologies provide a feasible solution for WSN mote power supply. This method

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"harvests" various forms of environmental energy such as vibration (Zhu et al., 2012a), thermoelectric (Im et al., 2012) and solar/light (Wang et al., 2012) into electricity to power WSN mote. The power management circuity of energy harvester stores the energy in electric double-layer capacitor (supercapacitor) or thin film solid state battery and utilizes the energy when needed. The utilization of the small but "infinite" ambient energy provides a potentially indefinite battery lifetime for WSN systems. Recently the concept of multiple sources energy harvesting has been proposed to harvest energy from more than one type of energy (Weddell et al., 2013).

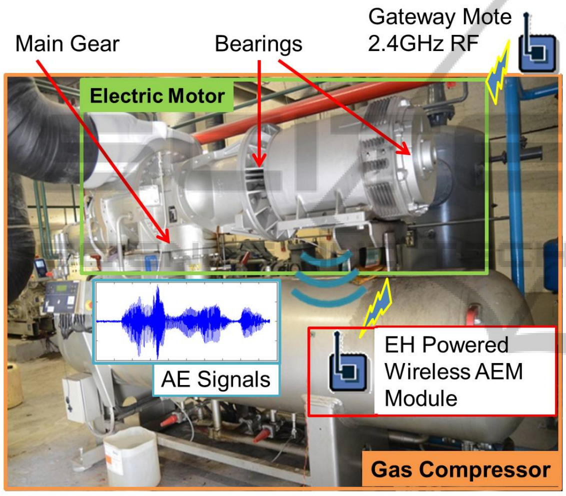

Figure 1: Energy Harvesting Powered Wireless AEM Module for Gas Compressor Monitoring.

By integrating and optimizing the three key technologies: 1) AE sensing, 2) Wireless sensor system, and 3) Energy harvesting, a new type of machinery preventive maintenance system is proposed. This paper introduces a vibration/thermoelectric/light powered wireless sensor module based acoustic emission monitoring system for rotating machinery fault detection application. Fig.1 illustrates the application of this proposed system in gas compressor monitoring.

The remainder of this paper presents the working principal, prototype implementation and the preliminary results of the proposed system. Section 2 summarizes related work in the area of machinery monitoring and energy harvesting powered WSN systems. Section 3 introduces the system architecture and subsystems. The first part of Section 4 presents the AE sensor and related signal processing. The rest part of Section 4 shows the multiple-source energy harvesting system and power management circuits. Section 5 demonstrates the prototype implementation and the preliminary test results as of April 2013. Final section concludes the main findings and planned future work.

2 RELATED WORK

The concept of rotating machinery monitoring has been addressed in many publications and and implemented in many commercial products. The most widely used method of NDT is vibration monitoring (VM) in the past 50 years (McFadden and Smith, 1984), (De Silva, 2010). More recently, the method of Acoustic Emission Monitoring (AEM) has been employed for PM applications. Compared with conventional vibration monitoring methods, AEM shows several advantages:

a) A substantial drawback of VM is the vibration energy from other parts of the machine (e.g. shaft and cooling fan) is often several orders of magnitude higher than the vibration energy of the defect gear and bearing, i.e. low signal to noise ratio (SNR). Acoustic signal has been proved to have significantly improved SNR during fault detection (Bohse, 2013).

b) Since AE sensing is a non-directional/non-contact technique, AEM system has greater insensitivity in positioning sensors, which reduces the installation costs. In addition, fewer sensors are needed in AEM systems than VM systems (Loutas et al., 2011).

c) With VM system, when a significant change in vibration can be observed, the remaining lifetime of the gear/bearing is very short. However, for AEM system the acoustic emission generated during the formation of cracks can be detected in the relatively early stage (Mba and Rao, 2006). The advantage of early detection increases the chance of preventive maintenance when AEM is employed.

Due to these advantages, AEM technique has been increasingly adopted in recent years for machine and structure health monitoring applications.

In (Lédeczi et al., 2011), Ledeczi et.al. demonstrates a bridge structural monitoring system with AE sensors. The DSP unit in this implementation is based on a FPGA instead of low cost MCU due to the data processing speed concern in MCU. However, recent development of MCU towards higher speed shows that the data process capability can be met by advanced MCUs such as ARM Cortex-M4 (Rutzig, 2013). Weddell et.al. presented a tunable frequency electromagnetic transducer powered WSN system for vehicle ferry engine monitoring application (Weddell et al., 2012). Since the diesel engine features different vibration frequency from electric motors, the energy harvesting device is also different.

Lubieniecki and Uhl presented an work in the area of harvesting thermal energy from high speed rotating bearings(Lubieniecki and Uhl, 2012). It investigated the correlation between the rotating speed and the harvested thermoelectric energy based on their configuration. It has concluded that with a rotating speed of 6000 revolutions per minute, more than 35mW average power can be harvested from the thermoelectric generator (TEG).

3 SENSOR SYSTEM ARCHITECTURE

The prototype system block diagram is illustrated in Fig. 2. The system consists of four main building blocks: 1) Sensor Layer; 2) DSP & RF Module; 3) Energy Harvesting Module; 4) Expert System.

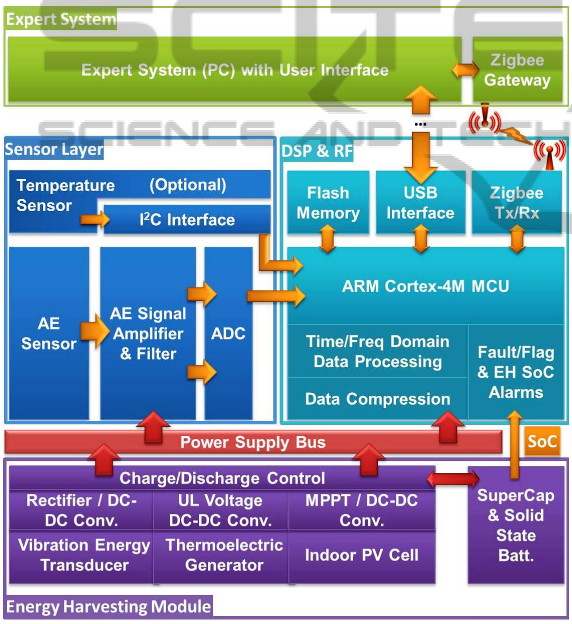

Figure 2: Energy Harvesting Powered Wireless AEM System Architecture.

The sensor layer for AE signal sensing includes AE sensors, amplifier, filter and ADC. It also has a I²C Interface for optional temperature sensors.

The DSP and RF module consists of ARM Cortex-4M MCU as the DSP unit, NXP JN5148 Zigbee wireless module for regular RF communication, flash memory and USB interface. The data processing is mainly based on fractional Fourier transform (FRFT) signal process. The results are compared with fault patterns to "flag" the possible fault. When the fault pattern is repeatedly detected, an alarm signal is sent to expert system for further investigation. The processed data is compressed and sent to expert system via the Zigbee module. Flash memory is used to temporarily store the data in the case of unsuccessful RF data transmission. USB interface is only used during system maintenance and possible upgrade.

The energy harvesting (EH) module includes 1) rectifier and DC/DC converter for electromagnetic (vibration) energy harvester, 2) ultra-low voltage (UL) DC/DC converter for thermoelectric generator (TEG), 3) maximum power point tracking (MPPT) for indoor photovoltaic cells (PV), 4) supercapacitor and solid state battery (thin film battery) as energy storage unit (ESU) and 5) charge/discharge control circuity to conditioning the input/output power from ESU. The ESU state of charge (SoC) is sent to MCU to monitor the condition of energy harvester.

The proposed prototype consists of four subsystem layers as shown in Fig.3 : Energy harvester power management layer, Sensor layer (amplifier/filter/ADC), MCU layer and Zigbee communication layer. Three AE sensors can be connected to this system.

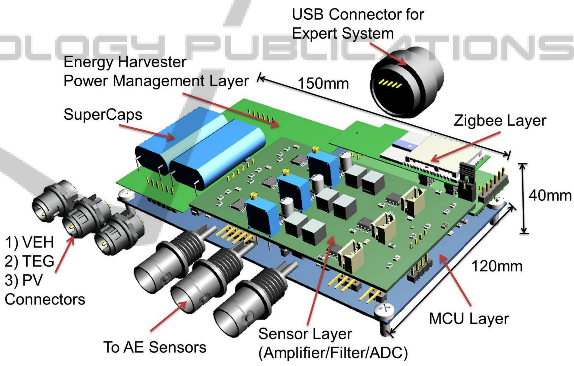

Figure 3: Energy Harvesting Powered Wireless AEM System Prototype 3D Illustration (the protection case is not shown in this illustration).

Vibration energy harvester (VEH), thermoelectric energy generator (TEG) and photovoltaic (PV) cells can be connected to the energy harvester layer. The main energy storage unit in this implementation consists of two 5F supercapacitors. The prototype (with IP45 protection case) is measured at 150mm×120mm×40mm. The ingress protection rating of the case is IP-54. All subsystems have been prototyped and manufactured as of April 2013.

4 ENERGY HARVESTING POWERED WIRELESS AEM SYSTEM DESIGN

The proposed prototype is the first version of the technology demonstrator. Before the integrating the subsystems into the final prototype, each subsystem is design and their performance is investigated. This section introduces the design of each subsystem.

4.1 AE Sensor System and Signal Processing

The condition monitoring system is essentially based on the feature extraction of AE signals. substantial efforts was concentrated on the signal processing of AE waveforms. Since the "fault pattern" of gear/bearing is the main diagnostic parameter, long term gear testing was conducted to identify the fault patterns in various frequency bandwidths. Fig.4 shows the test set-up of the gear surface/subsurface crack formation experiment.

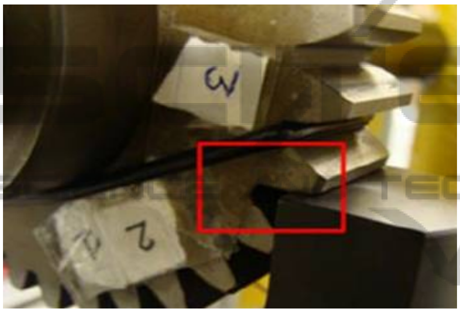

Figure 4: Gear Surface Crack/Wear Acoustic Test Set-up.

The area highlighted in Fig.4 is the root circle of a gear where the crack most likely to form. The AE fault pattern tests were conducted with several different types and stages of crack formations. A typical formed crack (late-mid stage) is illustrated and highlighted in Fig.5. The gear acoustic emissions test results are presented when the crack is excited by the contacts with other gear in Fig.5 (1-5).

Two types of data analysis techniques have been considered in this work: fractional Fourier transform (FRFT) and Daubechies wavelet (Grosse et al., 2002). Whilst the Fourier transform is only localized in frequency domain, wavelets are localized in both time and frequency domain. Daubechies wavelet with a 10-level signal decomposition may require more data processing than FRFT (Ching et al., 2004). Fig.6 shows the detected fault pattern at 200KHz when the late-mid stage of the crack is scanned with a 150KHz-300KHz filter.

Low power consumption of data processing and transmission is a main challenge in the design of AE WSN system. The MCU based device consumes 80-180mW power during "active" mode and 50μW "sleep" mode power. The power consumption of AE WSN mote is summarized in Table.1.

Since the harvested power from ambient environment is at 1mW level, the AE WSN system is programmed to perform duty cycling operation (periodic active-sleep-active cycles) in order to minimize average power consumption. On average, the active mode time is approximately 1.37 seconds followed by the sleep mode time of 1 to 10 minutes in the tests. The average power consumption ranges from 0.22mW to 1.76mW subject to the operational duty cycles.

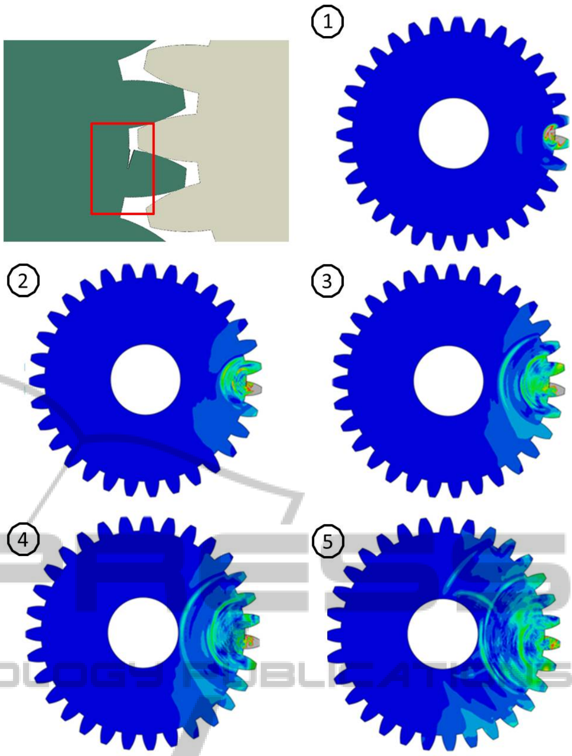

Figure 5: Gear Crack Formation and Acoustic Emissions Signal When Excited by the Contacts with Other Gear (1-5).

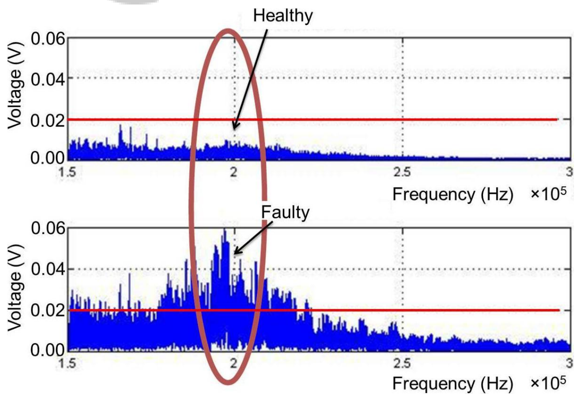

Figure 6: Gear Fault (crack) Pattern in Frequency Domain Analysis 150-300KHz FRFT Results.

Table 1: Power Consumption of AE WSN Mote (T_S : sleep mode time).

AE Power Consumption	Power (mW)	Time (Sec)	Energy (mJ)
Sleep Mode	0.047	60.00	2.820
Data ACQ (3 AE Sensors)	188.1	0.020	3.760
Data FRFT & Compression	76.26	0.920	70.16
Diagnosis Algorithm	86.16	0.210	18.09
RF Transmission	61.38	0.220	13.50
Total (1min T_S)	1.760	61.37	108.3
Total (3 mins T_S)	0.620	181.3	113.9
Total (10 mins T_S)	0.220	601.3	133.7

4.2 Multiple Source Energy Harvesting

Energy harvesting is proposed in this work to collect environmental energy and convert the harvested energy into usable form (Power/Voltage/Current etc.). On-site experiments had been carried out to investigate the available ambient energy sources in an industrial cold store facility. The mechanical vibration energy and surface temperatures on various positions of the main air compressor units (shown in Fig.1) have been measured to study the “harvest-able” energy. In this characterization, 0.025g to 0.05g vibration has been detected in addition to the 60 - 70 ^oC surface temperature on the rotary screw air compressor (near the air outlet).

Based on the characterization, thermoelectric energy harvesting is proposed in this work. Thermoelectric generator is a device that utilizes Seebeck effect which directly converts temperature difference into electricity (Ramadass and Chandrakasan, 2011). Thermoelectric materials high in positive/negative Seebeck coefficient such as Bi_2Te_3 are prepared into P and N types of thermo-elements. One P type and one N type thermo-elements are then connected in series via (copper) contacts as shown in Fig.7. In this configuration the P/N thermo-elements are connected in parallel from heat transfer perspective and a pair of thermo-elements forms a thermo-couple.

One thermo-couple can only generate small voltage difference (1-2mV) when 50-100^oC temperature is applied on the “hot” side of TEG. An array of thermo-couples are used to form a TEG module which normally consists of several hundreds thermo-couples.

Fig.8 shows a Bi_2Te_3 based TEG module with P/N type thermo-element measured at approximately $1mm^3$. In this module, 255 thermo-couples are used

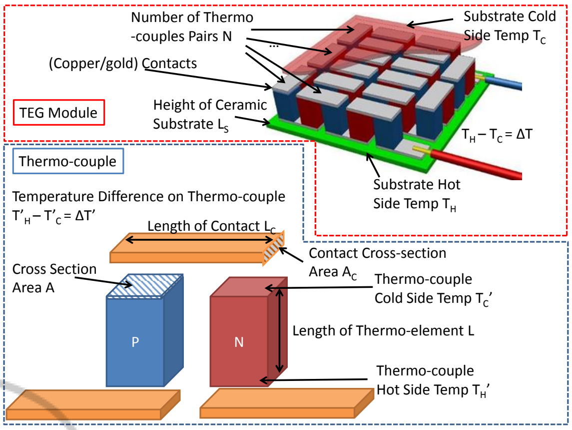

Figure 7: Thermoelectric Generator (TEG): Thermo-Couple and TEG Module.

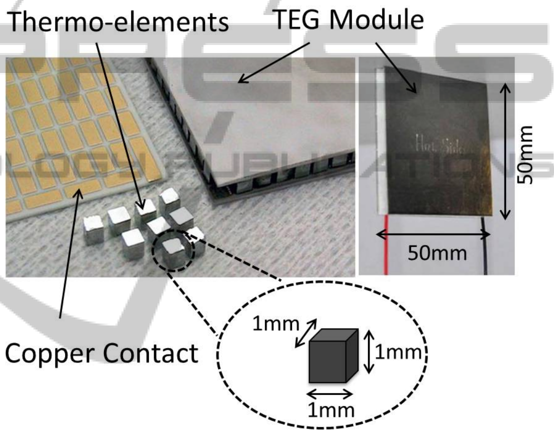

Figure 8: TEG Module.

to form this TEG, connected via copper contacts and supported with ceramic substrates. This type of TEG is tested with hot side temperature ranging from 50^oC to 80^oC. Passive heat sink (similar to typical CPU heat sink) is mounted on the cold side of TEG with thermal compound applied on the interface between TEG and heat sink. The measured results of thermoelectric generator are summarized in Table.2.

Table 2: TEG Characterizations Results at Matched Load.

Heat Source Temp (^oC)	50	60	70	80
Module Temp Diff. ΔT (^oC)	2.5	4.0	5.5	7.5
Measured Voltage (V)	0.212	0.336	0.464	0.632
Measured Max. Power (mW)	1.384	3.544	6.704	12.46

The generated voltage on the load is between 0.212V to 0.632V in this test. This voltage is lower than the minimal start-up voltage of most boost converters. This work adopts a power management design based on Texas Instruments BQ25504 energy harvesting chipset. BQ25504 features a start-up voltage of 40mV. BQ25504 requires a start-up current of several mA in order to obtain a 1.8V power supply voltage on the storage capacitor. A maximum power point tracking (MPPT) function adjusts the duty cycle of boost converter in order to match the input impedance of the boost converter to the TEG internal resistance, thus, a matched impedance. In this work, an additional load switch and an output voltage regulator (buck/boost converter) are used to supply a regulated 3.3V voltage output. The load switch and the enable pin ($\overline{SHDN}$) of the buck/boost converter are controlled by "VBAT_OK" pin (Digital battery good indicator) of BQ25504. In this way, the buck/boost converter only starts up when BQ25504 is fully operational. Therefore, the cold start issue of buck/boost converter can be avoided.

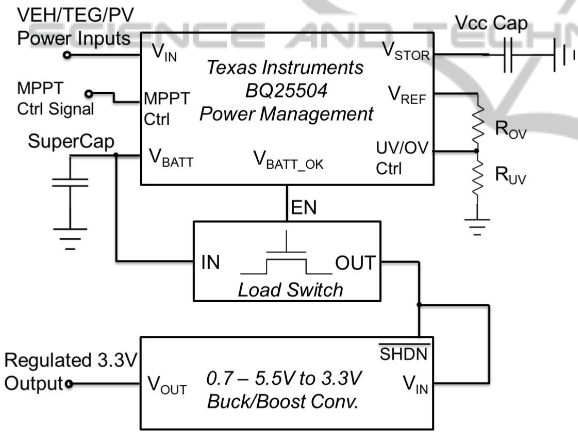

Figure 9: Schematics of Energy Harvester Power Management Circuit.

In addition to the thermoelectric energy harvesting, vibrational energy is widely available in the targeted deployment scenarios. In electrical motor systems, the vibration frequency is highly dependent on the mains frequency (power line frequency). In this measurement, as shown in Fig.10, the resonant frequency peaks around 50Hz with 48mg acceleration.

The electromagnetic vibration energy harvester adopted in this design is Perpetuum FSH module (Zhu et al., 2012b). The AC power generated from the energy harvester is rectified by the Perpetuum FSH module internal full bridge rectifier. The DC/DC power conditioning of the vibration energy harvester is also BQ25504. The main difference is the MPPT circuit is by-passed in this design.

A low voltage indoor photovoltaic power management circuit is also built in this design with BQ25504.

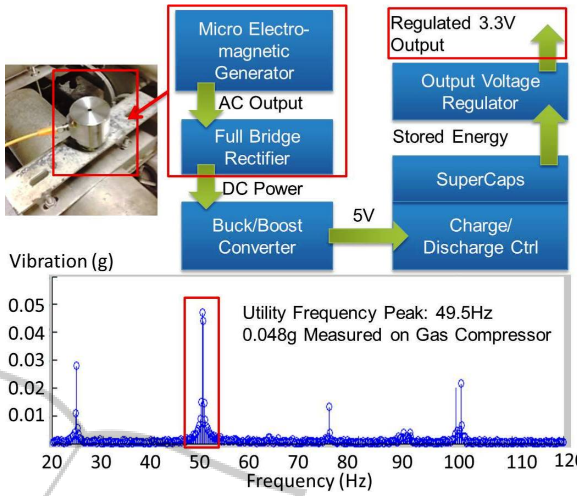

Figure 10: Vibration Energy Harvester Power Management and Measured Vibration of Air Compressor.

Different from impedance match in thermal electric energy harvesting, the maximum power point voltage of PV cell is around 76% of its open circuit voltage (O'Donnell and Wang, 2009). The MPPT control signal of BQ25504 is adjusted accordingly for the PV energy harvesting.

The multi-source energy harvester prototype is implemented and tested on the air compressor unit to verify the feasibility and functionality of the proposed design. The energy harvester prototype and its test results are presented in next section.

5 PROTOTYPE DEPLOYMENT AND PRELIMINARY RESULTS

The energy harvester for powering AE system prototype was tested on an industrial air compressor in a large scale cold store facility. Accelerometer and thermo-couples are used to measure the temperature and vibration at various part of the air compressor. The data is recorded using a portable Picolog-1000 data acquisition system with labview interface. The purpose of this deployment study is to determine the suitable deployment position of energy harvester for AE systems. The optimal position where energy harvesters can be deployed to is on the air-oil separator of the air compressor.

The temperature measured on the outlet is measured at 69^oC and 62^oC on the surface of the air-oil separator. The vibration energy is measured at between 0.025g and 0.048g at 49.3Hz to 49.7Hz frequency during the experiment (when compressor is operating). The deployment characterization of energy harvester is illustrated in Fig.11.

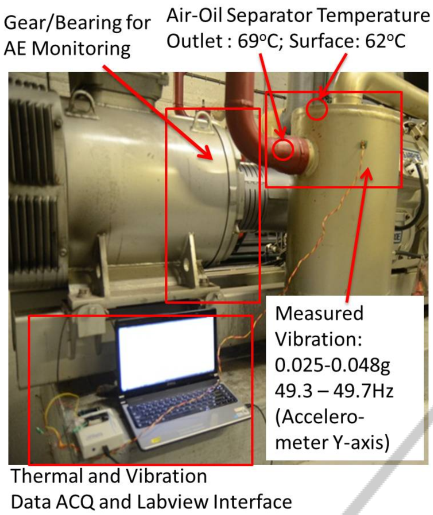

Figure 11: Energy Harvester Powered AE System Deployment Characterizations.

The energy harvester prototype is then deployed on the top of air-oil separator. The result verification is based on the storage capacitor charging characterization. The thermoelectric and vibrational energy harvesters are connected to the power management circuit in order to charge the 0.47F supercapacitor. When charging the capacitive load, the average charging power P_{avg} can be calculated as,

$$P_{avg} = \frac{C_{SC} \cdot V_{target}^2}{2 \cdot T_{chrg}} \tag{1}$$

where C_{SC} is the super-capacitor capacitance, T_{chrg} is the total charging time.

The supercapacitor charging experiments were conducted on TEG and vibration energy harvester (VEH). The results are shown in Fig.12.

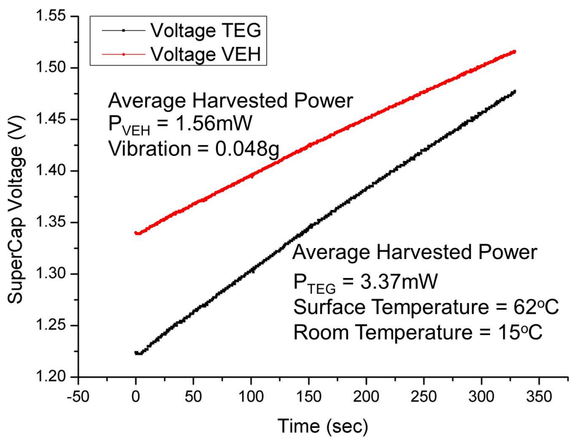

Figure 12: VEH and TEG Energy Harvesters Supercapacitor Charging Experiments.

The room temperature in the experiment is 15^oC. The hot side temperature of air-oil separator is 62^oC. The supercapacitor is charged from 1.22V to 1.48V within 325 seconds. The average harvested power of TEG is calculated at 3.37mW.

When the VEH is excited with 48mg acceleration at 49.5Hz, the harvested power charges the supercapacitor from 1.34V to 1.52V in 325 seconds. The harvested vibrational power is 1.56mW on average during the charging process. The combined harvested power is calculated at 4.93mW when the air compressor is operational.

By revisiting the power consumption profile of AE WSN module in Table.1, the harvested power 4.93mW is sufficient to power AE WSN module to operate with 1 minute measurement intervals (1.76mW). The minimal measurement interval of AE WSN module is calculated at 20 seconds, i.e. the multi-source energy harvester enables the AE WSN module to perform fault detection every 20 seconds.

6 CONCLUSIONS

Acoustic emissions monitoring system has demonstrated several advantages over the conventional vibration monitoring system for the application of gear/bearing fault detections. Micro-controller based wireless sensor networks (WSN) technologies significantly reduce the material and installation cost of industrial monitoring systems. Therefore, an approach to conduct AE monitoring with WSN modules is proposed in this work.

A main bottleneck for this type of system is the mote power consumption can deplete the battery within several months of deployment. An energy harvesting subsystem, which can harvest thermal, vibrational and light energy, is then presented in this paper to power the AE WSN mote with ambient energy.

The feasibility of powering AE WSN mote entirely from energy harvesting is investigated in this work. When deployed on an air compressor, the proposed power management circuit shows that it can harvest 3.37mW from wasted heat and 1.56mW from machine vibration, then store the energy in supercapacitor type energy storage unit. The hybrid energy harvesting subsystem generates 4.93mW when the air compressor is operational. Based on the AE system power consumption characterizations, the harvested power is sufficient to perform AE fault detection every 20 seconds and achieves power autonomy in the air compressor experiments.

All subsystems of the AE WSN system have been built. The current system is under tests to verify the reliability in real-world condition. Being a first-generation prototype, the prototype device is undergoing an optimization process from power consumption/management, data processing and diagnose algorithm perspectives.

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