Low Cost Wireless Vibration Monitoring using Thermoelectric Energy Harvester for Machinery Prognostic

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ABSTRACT

This paper presents a microphone-modified low cost vibration sensor that can be operated by a self-battery system using a thermoelectric generator. The developed microphone-based vibration sensor with two batteries for the efficient use of electric power from the thermoelectric element was integrated as a wireless sensor node. The sensor accuracy was calibrated in two operations. One was an experimental setup to evaluate the frequency dependence of the developed sensor by using waves of a specific vibration compared with piezoelectric accelerometers. The second operation was long term data acquisition in real field. We successfully demonstrated the wireless vibration sensing operation for a motor in real field. It was operated only their sensing and transmitted energy by itself using its surface temperature difference for two months. The raw vibration data was sensed and acquired for two months, and the feature values of the results of time series data were in good agreement with the referenced piezoelectric sensor data.

1. INTRODUCTION

The data-driven machine fault prognostics are one of the important fields for Internet of Things application. Vibration data is one of the important parameters for machinery condition monitoring due to its wide range of prognosis for machine health state. However, most of conventional machines such as motors, pumps are not so cost-effective when it comes to maintenance. Therefore, cost-effectiveness compared with man-hour was one of the most important problems that resulted in the spread of the machine monitoring system.

There were two strategies to achieve a total cost reduction. One is to reduce sensor cost. The other is to reduce the maintenance cost such as battery replacement. The wireless sensor node for vibration sensing is an acquisition system that is expected to reduce the maintenance cost. Shaikh, Zeadally, (2016) reported that a self-powered wireless monitoring system was one of the key technologies to reduce the battery replacement cost and increase its life time simultaneously. Niedermayer, Bennecke, Wirth, Armbruster, and Lung (2014) reported the system design about vibration monitoring in paper manufacturing motor using vibration and thermal harvesting devices. Stojcev, Kosanovic, Golubovic (2009) pointed out the needs for power management of energy harvesters using control of sensing time frequencies because of their unstable energy source. Dallago, Danioni, Marchesi, and Venchi (2012) reported the low power wireless sensing system using electromagnetic energy transducer.

In this study, we developed two concepts of cost reduction system for wireless vibration measurement on their machinery monitoring. One was a microphone-modified vibration sensor for low cost sensing unit. The other was a sensor system integrated with thermoelectric generator and wireless transceiver on 2.4 GHz in low power consumption for enough raw vibration data acquisition system.

2. SYSTEM ARCHITECTURE

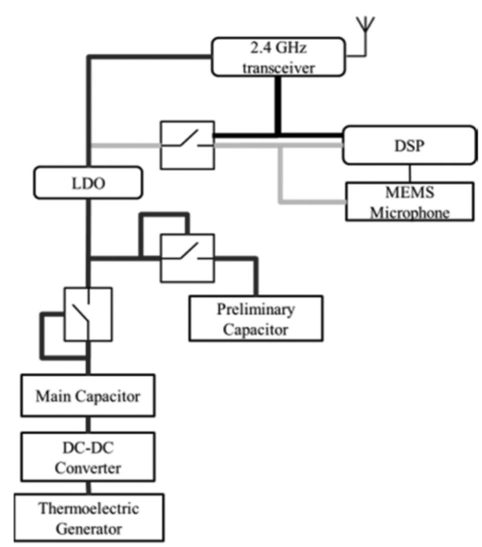

Figure 1. System architecture of wireless sensor node with thermoelectric generator

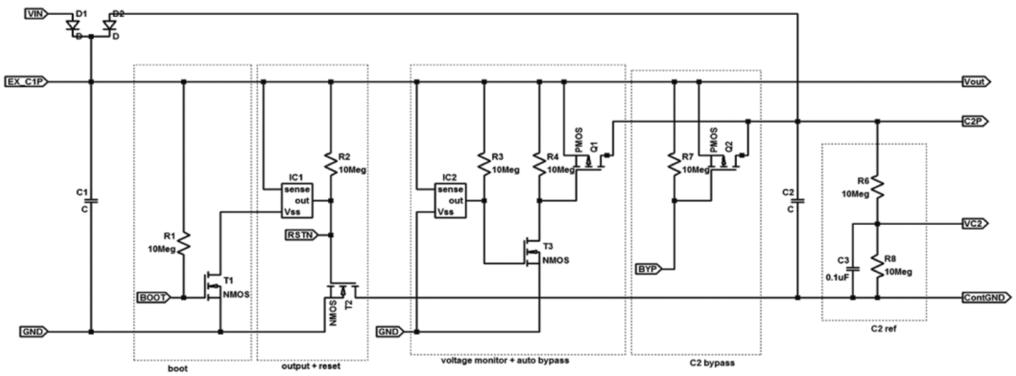

Figure 2. Electric circuit for control and conditions of sensor node.

Figure 1 shows the schematic of our systems architecture using a thermoelectric generator. The system composed of three parts. One was an accelerometer for vibration sensing. The second was a thermoelectric generator. The third was controller of the whole system and wireless transceiver. The goal of the design for this architecture was the acquisition of raw vibration data from 1 to 10 kHz due to its general vibration in condition monitoring frequencies. The power requirement was balanced between the thermoelectric generator and sensor node power consumptions. In many fields of pumps and motors, the operating machine surface temperature were more than 35°C, and atmospheric temperatures around the machine were between 15 and 30°C. An area of 25 cm^2 was the target due to machine surface area's limitation. The thermoelectric generator and sensor were separated based on the flexibility of position settings because the highest surface temperature position of machine is usually different from the sensing positions such as bearing failure monitoring.

Figure 2 shows the control circuit for battery. When power generation by the thermoelectric generator starts, charging of the main storage capacitor C1 via the diode D1 starts. When C1 reaches a constant voltage at 3.3 V, the switch T2 responds by the reset IC IC1, and the supply of power to a subsequent load starts. Moreover, when generation of power is achieved, and a relatively higher reference voltage at 4.5 V is reached, the C2 is connected in parallel to C1 through IC2 and switch Q1, and the capacitors functions as one with a synthesized capacity. According to this mechanism, IC1, IC2 are deactivated by performing a control to set the BOOT and BYP control signals to Lo after the supply of power to the microcomputer starts so that the operation is continued even when the voltage of C1 drops as compared to the respective reference voltages.

In the field of condition monitoring of machines, as vibration measurement devices piezoelectric accelerometer were generally used because of their wide range sensitivity. However, the piezoelectric accelerometers generally cost very high, and the power consumption are also high. Therefore, the other type of vibration sensor with low cost and power consumption is required strongly. One of the candidates was the microelectromechanical (MEMS) accelerometer which was used in smartphones. However, the accelerometer did not support a wide range of frequencies except for generally required frequencies for smartphones. Then, instead of MEMS accelerometer, we tried to apply the microelectromechanical microphone. The SPH0645LM4H-B digital I^2S MEMS microphone from Knowles Inc. was selected as the vibration sensor. In general, a microphone has cavities for air vibration measurement. However, the structure was meant to measure external sound. Therefore, in our settings, the cavity was filled, and the vibration of machines was directly transmitted to the sensor by the legs of the magnet. Figure 2 shows the calibration results of our settings at 1 kHz acceleration of microphone of general piezoelectric accelerometer 353B15 from PCB Piezotronics Inc. as a referenced piezoelectric accelerometer. Output from microphone was a voltage at the beginning so that it was necessary to obtain a coefficient that converted the value to acceleration. Setting of conversion coefficient was calibrated as 0.2 mV/G at 1 kHz acceleration from 353B15. Figure 3 shows results of acceleration from microphone and 353B15 when changing the value of acceleration. The dependency of the amplitude of accelerations was the same for the microphone and piezoelectric accelerometer in each amplitude values.

The thermoelectric generator was used bulk thermoelectric material-based conventional device GKB10 from Yamaha Corporation. The structure to obtain thermal energy as the temperature difference was also conventional, which composed of aluminum plate and heatsink, with a size of 6.25 cm^2 and a height of 5 mm. The temperature difference occurred between the machine surface temperature and the atmospheric air temperature. The basic voltage obtained from the structure was 0.2 mV/K. However, the generated voltage was unstable and had a lower value than that of electric circuit required. Therefore, the DC-DC converter LTC3109 from Linear Technology Inc. was used to obtain 5 V from thermoelectric voltage which was over 55 mV continuously.

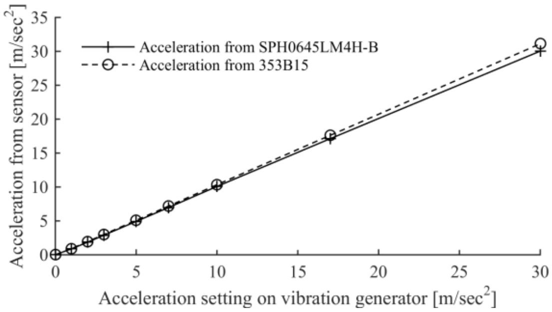

Figure 3. Calibration results of acceleration amplitude dependencies for PCB353 and MEMS microphone-modified sensor

3. RESULTS OF CONDITION MONITORING IN FIELD OF MOTOR

Figure 4 shows the setting conditions and positions of each device on a motor in real field. The microphone was set at the edge of the motor for sensing the bearing failure. The thermoelectric generator was set in the middle of the motor that was the highest-temperature position of the motor. Wireless units and circuit box were positioned near the motor.

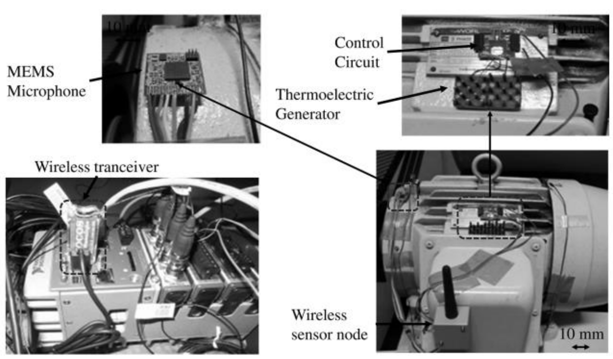

Figure 4. Schematics of position and settings of wireless sensor node and thermoelectric generators in three phase induction motor surface

Figure 5 shows the results of thermoelectric power generation of two modules, and the temperature difference between machine surface and atmospheric temperature during one day. The change of voltages was synchronized consistently with temperature difference. The open circuit voltage was attained more than 0.5 mV during the operation. The temperature difference depended on the machinery status change between on and off timing. From 800 to 1200 minites, the values were stable at room temperature fluctuation. The average electric power for one day cycle was 57.6 J/day, and it was enough to keep the sensor node operating.

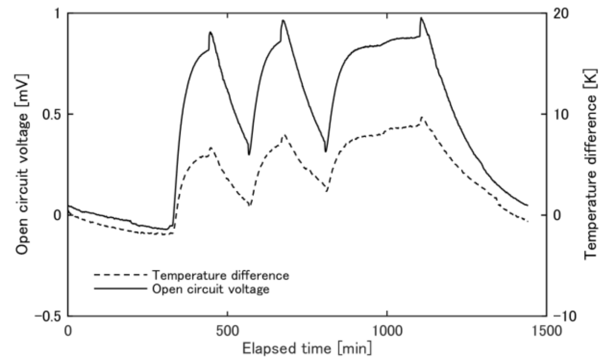

Figure 5. Themoelectric power generation and voltage in real field of data

Figure 6 shows the results of battery levels from the thermoelectric generator for one day from the charged state as shown in Figure 5. The capacitor voltage was cycled from voltage down and up, correlated with the measurement of vibration and transmitted to the transceiver. The measurement of vibration was carried out once in a day. In the initial timing from 0 to 200 minutes, the machines were not operated, so that the voltage were not charged and gradually decreased. When the machine operated in 200 minutes, the voltage were charged, and reached around 4800 [mV], which was the maximum voltage of capacitor. In the 450 to 500 minutes, the voltage was sudden drop. It was the sensing time of vibration. The means of this drop was large power consumptions were occurred in short time, and maintained voltage from 500 to 700 minutes. The gradually decreased voltage from 700 minutes was the same as initial. The machine was stopped and not operated. Its condition was the transmitted timing of the battery source from the capacitor due to stopping of the motor for a long time.

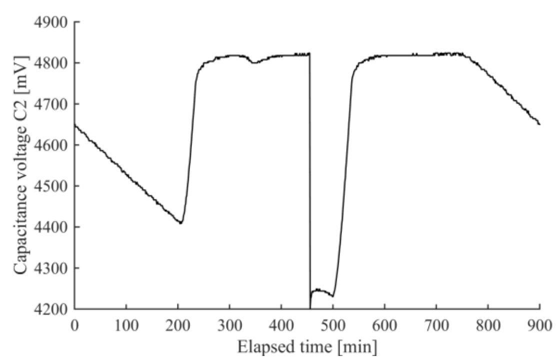

Figure 6. Capacitance voltage profile during duty-cycle operation for 1 day charged from thermoelectric generator only

Figure 7 shows the results of the overall values of acceleration by the piezoelectric accelerometer and the microphone-modified sensor from 1 to 10 kHz. The overall value was defined in ISO 13381 as the following equation from Fourier transformed integration. Both results were consistent with the high amplitude of acceleration. On the other hand, the low level amplitudes were different between the two sensors. This difference was caused by the noise level of the two sensors and their frequency calibration settings. The noise level from their spectral results was about 3dB in each frequency. Therefore, the use of a microphone may not be sufficient for low level amplitude of monitoring. However, it was useful for monitoring motor systems as a low cost sensing system.

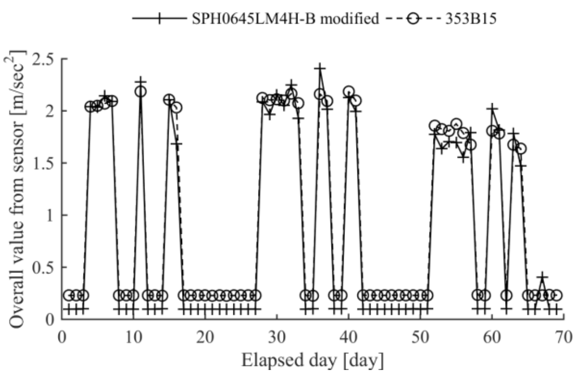

Figure 7. Results of long time data acquisition on real field motor using overall feature value

4. CONCLUSION

We successfully developed the wireless sensor node with thermoelectric energy harvester. The developed sensor could transmit the raw vibration data and was operated for two months. The monitored vibration was changed gradually in the same trend of referenced piezoelectric sensor. Therefore, we concluded that the developed sensor worked efficiently in the field of wireless monitoring system.

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BIOGRAPHIES

Takuya Nishino was born in Ehime, Japan, in 1980. He received the M.S degree in physics from Tohoku University in 2008. In 2008, he joined Fujitsu Laboratories Ltd., and worked for thermoelectric generator, analytics for machinery prognostics.

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