Integrated smart bearings for next generation aero-engines. Part II: energy harvesting and wireless communication development

Journal:	*WCCM 2017*
Manuscript ID	CM-MFPT-0393-2017
Topic:	Condition monitoring (CM) methods and technologies
Date Submitted by the Author:	21-Apr-2017
Complete List of Authors:	Zaghari, Bahareh; University of Southampton Faculty of Engineering and the Environment,
Keywords:	Energy harvesting, Aerospace, Condition monitoring

Integrated smart bearings for next generation aero-engines. Part II: energy harvesting and wireless communication development

Bahareh Zaghari[1,*], Alex Weddell[1], Neil White[1], Imran Bashir[2], Terry J. Harvey[2], and Ling Wang[2]

[1]Electronics and Computer Science, University of Southampton, Southampton, SO17 1BJ, UK
[2]National Centre for Advanced Tribology at Southampton (nCATS), Faculty of Engineering and the Environment, University of Southampton, Southampton, SO17 1BJ, UK
[*]E-mail: bahareh.zaghari@soton.ac.uk

Abstract

The robust and reliable operation of aircraft engines is paramount. Rolling element bearings play a major role in aircraft engines and bearing failure impacts engine health and reliability. Condition monitoring of the bearing system is necessary to provide early warning of problems by sensing parameters such as vibration and temperature. However, conventional wired sensing systems are not always desirable due to size and weight constraints, and their reduced performance in high temperature and pressure environments. For the development of innovative smart bearings for an Ultra High Propulsion Efficiency (UHPE) ground test demonstrator, an integrated, self-powered and wireless system is proposed. In this paper, the feasibility of using a self-powered sensor for this application is investigated. The design of the self-powered condition monitoring system addresses the issues of both achieving reliable sources of energy and transmitting data. Laboratory experiments are carried out to evaluate the performance of the system under various operating conditions. The effects of temperature variation on efficiency of the energy harvester are demonstrated.

1. Introduction

The integration of self-powered and wireless electronics in aircraft engines provides information from confined areas. In a confined rotating environment, such as a bearing, it is often not feasible to install a sensor using wires, and changing batteries can also be troublesome and costly due the resulting down time of the machine. Finding a robust and cost-effective technology that can be applied to or in the vicinity of a rotating system (a bearing) is the objective of this paper.

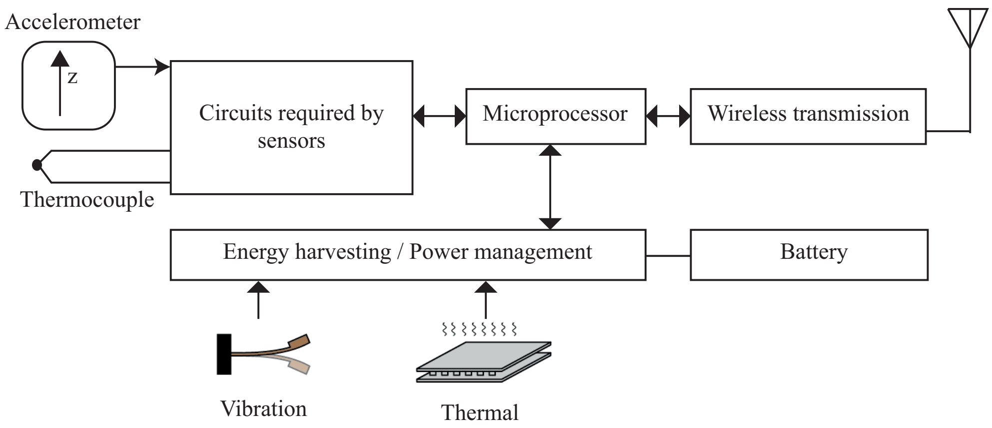

Figure 1: Schematic of the energy harvesting powered sensor system.

Energy Harvesting based systems are the result of providing wireless sensor network nodes with the capability of extracting energy from the surrounding environment. System architecture of a wireless node with energy harvesters is presented in Figure 1. A good example of commercial wireless system is the GE Bently Nevada wireless condition monitoring system, installed as a pilot at Shell's Nyhamna Gas Plant for predictive maintenance. The cost of hard wiring was excessive to monitor the plant, therefore a wireless system powered by vibration energy harvesters was used on a number of machines to provide full vibration data from accelerometers to the central data processing system [1]. Another example is a rail monitoring system implemented by Perpetuum, which includes sensor node contains a 3-axis accelerometer, vibration energy harvester, a temperature sensor, electronics and wireless radio communications. The Perpetuum system provides a bearing health index that allows the operator/maintainer to monitor bearing wear in real time [2]. In the aerospace industry, Health and Usage Monitoring System (HUMS) is a sensor based monitoring system that enables condition monitoring by measuring the health and performance of mission-critical mechanical components in aircraft. This device can be powered by energy harvester to record data from sensors, which are usually placed in construction area [3].

As the need for wireless communication in aircraft increases, emphasis on robustness, security, availability, and maintainability of wireless systems will also increase. In order to consider the wireless communication in the aircraft several major issues must be addressed such as certification of the new technology and especially in the case of wireless LANs electromagnetic interference concerns. Prior to considering how to build robust and secure wireless networks, it is important to understand how well wireless networks operate in a jet engine. Wireless transmission through metal in a jet engine is one of the challenges. Also, providing power to transmit data needs to be calculated based on the duty cycle of the sensors.

Transmitting power without wires can be beneficial for powering an array of wireless sensors. The currently available wireless power transfer techniques can generally be classified into radiative and nonradiative modes. In radiative modes, radio-frequency transmission uses antennas to transmit power. The radio frequency transmission requires some electronics that operate only at low temperature. Nonradiative modes use inductively coupled transformers that can operate in high temperature, but only work in close-range across a small gap. However a wireless power transfer technology, commonly called wireless electricity [4, 5], has recently been demonstrated as reliable. This technique is based on nonradiative strongly coupled magnetic resonance in the mid-range, defined as several times the resonator size. In reference [4], two identical coils were exploited as wireless electric resonators, a 60 watt bulb was fully illuminated wirelessly seven feet away from the power source with a power transfer efficiency of 40%. Using self-resonant coils in a strongly coupled regime, they showed experimentally an efficient nonradiative power transfer over distances up to 8 times the radius of the coils. This system also works well even when the line-of-sight between the two resonators was blocked by a nonresonant object, yet was almost non-respondent to nonresonant objects. Despite significant developments, current approaches are still limited to the mid-range transfer [6]. For small coils in particular, solid obstacles restrict power transmission.

Inductively coupled coils and the Electromagnetic Acoustic Transducer (EMAT) are used in literature to transfer data through a metallic wall. However, in these methods permanent magnets are used [7]. An alternative technique is piezoelectric wedge transducer. Based on the position of the piezoelectric, different type of waves can be generated, which can travel through a metallic wall. The main benefit of acoustic power transfer with piezoelectric transducers is that piezoelectric wedges are suitable for use with a much wider range of materials in high temperature compare to EMATs. Disadvantages include attenuation, the coupling dependence and implementation in the bearing. Reverberation can add complexity to data processing.

In this paper, an overview on energy harvesting from sources available in the jet engine is presented, which also discusses how different transduction methods convert ambient energy into electrical energy. As the aircraft engine experiences temperature changes, for example during take-off and landing, energy harvesting from waste heat can be considered. A Thermoelectric Generator (TEG), which converts heat energy to electrical energy, is proposed for the development of the smart bearing in Sections 3 and 4. This energy harvester is required to fulfil several criteria including: (1) The avoidance of devices that generate magnetic fields that could potentially trap metallic debris around the bearing. (2) Ability to operate at high temperature ($>$250°C), and in dirty and encapsulated environments. Hence certain traditional energy sources such as sunlight and radio frequencies are not investigated. (3) Robustness at high temperature when it is mounted in an environment containing a mixture of air and hot oil, (4) Limited size of the TEG, which depends on the assembly location and (5) sufficient power density to power sensors and necessary electronic devices. Several TEG designs are described in the literature to power sensors in aircraft pylons [8], the aircraft hull [9], and in aircraft bearing [10]. In this paper, we introduce a TEG which can provide power to store data from sensors (e.g accelerometers and thermocouples) in the smart bearing for an Ultra High Propulsion Efficiency (UHPE) ground test demonstrator. Experimental results are shown to demonstrate the performance of a commercial TEG (see Section 5).

2. Vibration energy harvesting

The choice of a suitable energy harvesting method and harvester design is very important. Maximum volume or weight of an energy harvester is usually a limiting factor. Therefore the design of the energy harvester system has to be optimized to maximal efficiency and required power. The conversion mechanisms that have been widely reported in the literature for converting mechanical energy to electrical energy are the piezoelectric and electromagnetic [11–13].

Piezoelectric materials change with the direction of forces and orientation of the polarisation and electrodes [14]. The piezoelectric effect exists in two forms: the direct and the converse effects. The direct effect describes the ability of the material to transform mechanical strain into electrical charge, whereas the converse effect converts an applied electrical potential into mechanical strain energy. Piezoelectric materials have been used widely in energy harvesting as they are relatively simple to implement, however they also have high output impedance, which makes it difficult to couple with electronics efficiently. The piezoelectric transduction efficiency is limited by the material of the piezoelectric element; this affects the optimal power that can be harvested and limits the maximum operating temperature. Piezoelectric energy harvesters have a low average lifetime of less than a year and they highly sensitive to the vibration frequency of the source as the efficiency drops dramatically when the source vibration frequency does not match the harvester frequency, hence piezoelectric materials are not suitable for the smart bearing design.

Electromagnetic induction is based on Faraday's Law, which dictates that an electrical current will be induced on a closed circuit when the magnetic flux through a surface bonded by the conductor changes [15]. In electromagnetic energy harvesters, permanent magnets are used to produce strong magnetic fields, and metallic coils are used as conductors. The electrical energy is generated by either the relative movement of the magnet with the coil, or because of a change in the magnetic field. In the former case, the relative motion between the coil and the magnetic field causes a current to flow in the coil. The voltage induced to the coil, known as electromotive force (EMF), is proportional to the strength of the magnetic field, the velocity of relative motion, and the number of turns in the coil [16]. The output power generated by the electromagnetic transducer is affected by design factors. The size, material properties, and geometric configuration of the magnet and the coil changes the output power. A strong permanent magnet is present and the efficiency of the harvester is highly sensitive to vibration frequency of the source. Owing to the demagnetization of magnets at high temperature and the restriction of using magnets in bearings, this technique cannot be implemented.

3. Thermal energy harvesting

A Thermoelectric generator converts heat energy to electrical energy through a phenomenon called the Seebeck effect [17]. In TEG when the connected junctions of two dissimilar materials (n-type and p-type) have a temperature difference, an electrical current is generated [18]. An electrical circuit for a unit couple of a TEG is shown in Figure 2. The TEG efficiency depends on the thermoelectric figure of merit ZT of its material components, which is a function of the Seebeck coefficient S, electrical resistivity ρ, thermal conductivity κ, and absolute temperature T. The most widely used commercial thermoelectric material is bulk Bi_2Te_3, which has $ZT = \frac{S^2T}{\rho\kappa} \approx 1$ [19]. TEGs have higher efficiency when temperature difference between the cold and hot side is greater [18]. A thermoelectric generator is an ohmic device. For best performance it is important to use an ohmic load with an electrical resistance that matches the resistance of the generator. The output power of the system depends on the ratio of the electrical resistance of the generator and the load. The electrical resistance of the generator depends on the temperatures of the hot and the cold side.

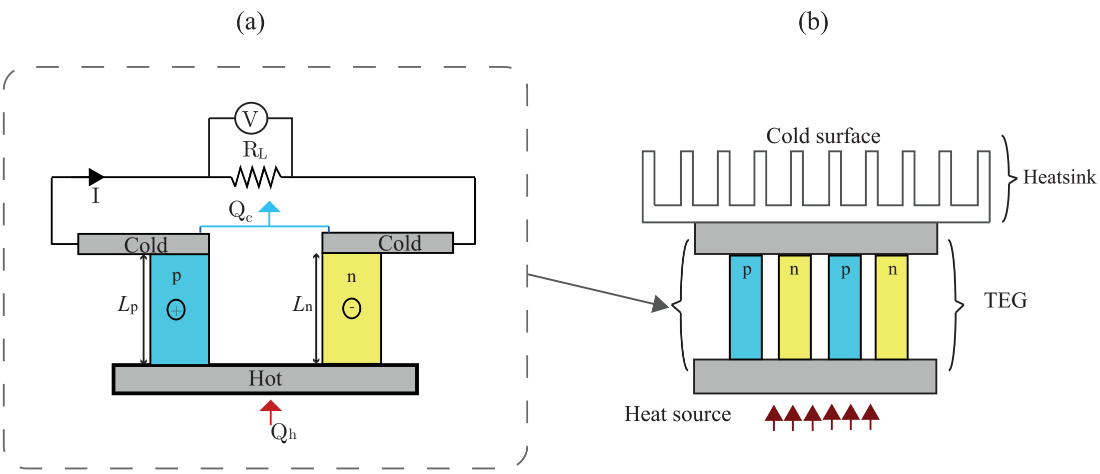

Figure 2: (a) An electrical circuit for a unit couple of a thermoelectric generator. (b) The thermoelectric generator between the heatsink and a hot surface.

For a thermoelectric generator, the magnitudes of the heat input and output are presented with Equations 1 and 2 as follows [20]

$$Q_{\mathrm{h}} = ST_{\mathrm{h}}I - \frac{1}{2}I^2R + K(T_{\mathrm{h}} - T_{\mathrm{c}}), \tag{1}$$

$$Q_{\rm c} = ST_{\rm c}I - \frac{1}{2}I^2R + K(T_{\rm h} - T_{\rm c}), \tag{2}$$

where $Q_{\rm h}$ is the thermal input from an outside heat source, $Q_{\rm c}$ is the thermal output to the cold source, $T_{\rm h}$ and $T_{\rm c}$ are the temperatures of the hot and cold sides, I is the current generated in the TEG, S is Seebeck coefficient,

$$S = S_{\rm p} - S_{\rm n}, \tag{3}$$

internal resistance R is [20]

$$R = \frac{\rho_{\rm p}L_{\rm p}}{A_{\rm p}} + \frac{\rho_{\rm n}L_{\rm n}}{A_{\rm n}}, \tag{4}$$

and K is [20]

$$K = \frac{\kappa_{\rm p}L_{\rm p}}{A_{\rm p}} + \frac{\kappa_{\rm n}L_{\rm n}}{A_{\rm n}}, \tag{5}$$

where A is the cross section area and L is the length of the leg couples as shown in Figure 2. Superscript n and p refers to n-type and p-type materials. By applying the first law of thermodynamics, the electric power W generated from the thermocouple is

$$W = Q_{\rm h} - Q_{\rm c} = SI(T_{\rm h} - T_{\rm c}) - I^2R = I^2R_{\rm L} \tag{6}$$

where $R_{\rm L}$ is the load resistance and R is the internal resistance of the TEG. Moreover, based on Ohm's Law, the voltage across the load is

$$V = IR_{\rm L} = S(T_{\rm h} - T_{\rm c}) - IR. \tag{7}$$

Therefore, current I is equal to

$$I = \frac{S(T_{\rm h} - T_{\rm c})}{R_{\rm L} + R}. \tag{8}$$

The open circuit voltage $V_{\rm oc}$ across the TEG can be calculated from

$$V_{\rm oc} = S(T_{\rm h} - T_{\rm c}). \tag{9}$$

The analyses presented so far represent the concepts of the thermoelectric generator of one thermocouple where multiple couples are being used in many of the TEG applications. In order to obtain the thermoelectric parameters for multiple leg couples (Figure 2), the unit couple parameters need to be multiplied by the number of leg couples, N, as follows

$$\dot{W}_{\rm N} = N\dot{W},\ \ (\dot{Q}_{\rm h})_{\rm N} = N\dot{Q}_{\rm h},\ \ (\dot{Q}_{\rm c})_{\rm N} = N\dot{Q}_{\rm c},\ \ R_{\rm N} = NR,\ \ K_{\rm N} = NK,\ \ V_{\rm N} = NV,$$
$$(V_{\rm oc})_{\rm N} = NV_{\rm oc},\ \ (R_{\rm L})_{\rm N} = NR_{\rm L},\ \ I_{\rm N} = I. \tag{10}$$

4. TEG experimental set-up

A thermoelectric module (type HZ-2 from Hi-Z) was assembled on a plate and a heatsink (from Alpha Novatech) was placed on the cold side of the TEG. Two k-type thermocouples and

MAX31855 cold-junction compensated thermocouple-to-digital converters were connected to the microcontroller in order to read the temperature of the hot and cold side of the TEG. The schematic of the experimental set-up is shown in Figure 3. A microcontroller (MSP432 series from Texas Instruments) was used to record the temperature data and open circuit voltage of the TEG. In this study the TEG is employed for an environment with time-varying temperature differences, therefore it is important to adjust the electrical operating point in order to maximize the harvested power. Maximum Power Point Tracking (MPPT) is considered in order to maximize the power extracted from TEG. A low power boost converter with battery management (type bq25504 from Texas Instruments) was selected. This MPPT circuit obtains a new reference voltage every 16 s by periodically disabling the charger for 256 ms and sampling half the TEG's open-circuit voltage (V_{oc}). This was implemented to convert the variable low voltage input from the TEG to a constant voltage level of 3.3 V. The energy is stored in a coin type rechargeable battery (battery charge is $3.4\text{V} \pm 0.15\text{V}$).

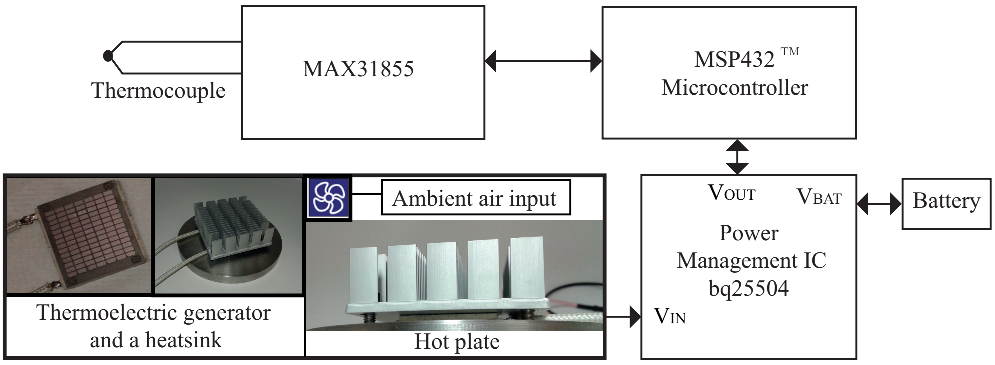

Figure 3: Schematic of the thermoelectric generator and powered sensor system.

5. Experimental results and discussion

The TEG with a heatsink on top was placed on a hot plate (Figure 3). The temperature of the hot plate was set to three different values at three stages. The room temperature was 24.7°C. The temperatures of the cylindrical plate (hot side) and heatsink (cold side) were measured every 10 seconds with the microcontroller. The voltage was measured across the TEG connection. Figure 4 shows the measured temperature results from this experiment. After 100 seconds, the hot plate was heated to 100°C and the tempearture of the hot plate was increased by 50°C twice after a further 3400 and 6650 seconds. At 10000 seconds the hot plate was turned off and the temperature of both sides were reduced to room temperature.

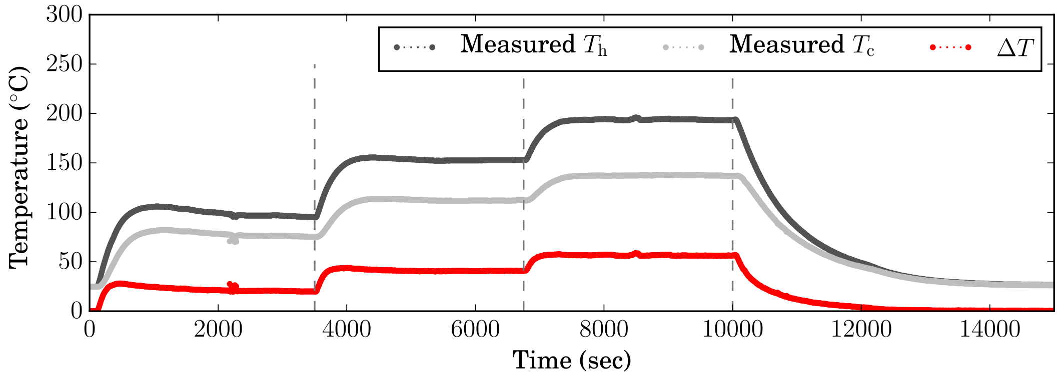

Figure 4: Measured temperatures from the hot side (T_h) and cold side (T_c) of the TEG and their differences (ΔT). The vertical dashed lines indicate where the hot plate temperature settings were adjusted. The measured data was recorded every 10 seconds.

Figure 5 demonstrates the open circuit voltage across the TEG is increased as the temperature difference was changed. The open circuit voltage was calculated from Equation 9 based on the Seebeck values provided from the HZ-2 TEG at different measured temperatures. In Figure 6 voltage at the discharged battery was increased to its maximum voltage when the temperature difference reached to 25°C and the open circuit voltage was equal to 0.3V.

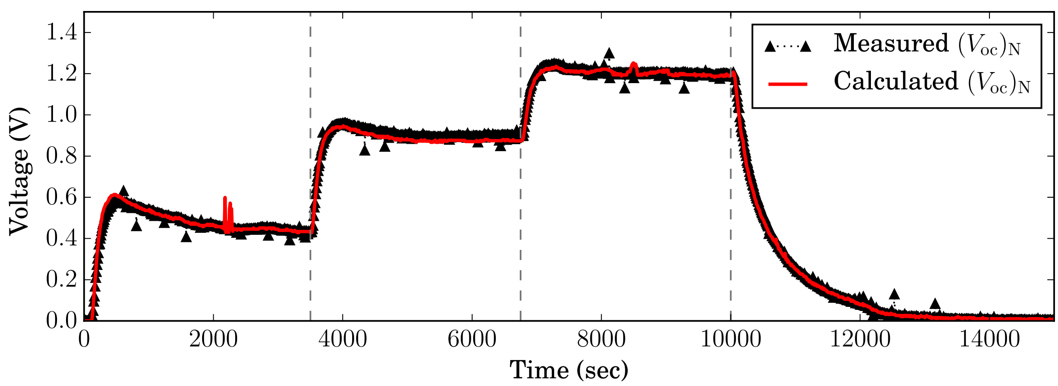

Figure 5: Measured and calculated open-circuit voltage of the TEG. The vertical dashed lines indicate where the hot plate temperature settings were adjusted.

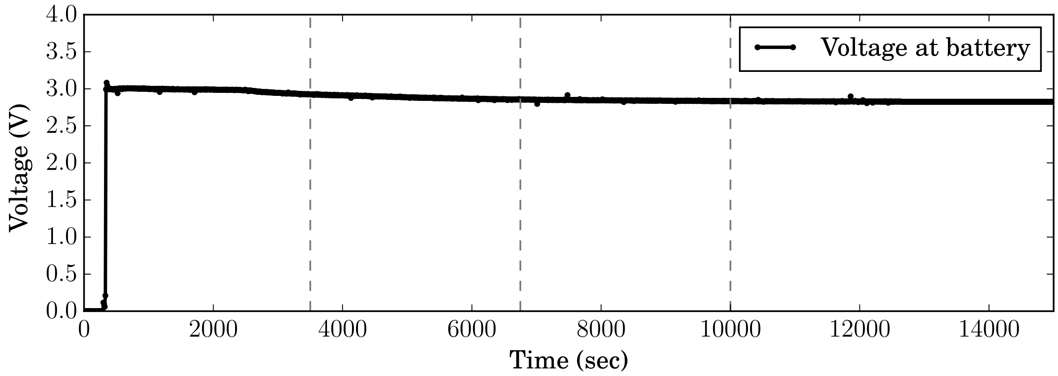

Figure 6: Measured voltage at the battery. The vertical dashed lines indicate where the hot plate temperature settings were adjusted.

The TEG introduced here can be used to provide power to record data with the low power microcontroller from accelerometers and temperature sensors. The efficiency of this system depends on the duty cycle of the data recording. For example, consider an accelerometer which is active for 1 minute and that requires 6000 mW power. If this sensor is active for 1 second every 10 minutes then the power consumed by the sensor is 10 mW. For every data transfer from the thermocouples and recording data by the microcontroller $\approx$ 10 mW at 3V was consumed. This was measured with a DC power analyser (model N6705 from Agilent Technologies).

6. Conclusions

The test and verification of the harvester is an important step in the development process of a smart bearing system with wireless sensors. It was demonstrated that sensors and the microcontroller can be powered by Thermoelectric Generators (TEG) due to very high thermal gradient available in the bearing system. This paper presented the open-circuit voltage measurement of a TEG at different temperatures. The low-power and low-cost microcontroller were used to demonstrate power consumption for recording the open-circuit voltage every 10s. Future work will focus on comparing different cooling mechanism for increasing the open-circuit voltage across the TEG, and on controlling the MPPT with the microcontroller in order to increase the efficiency of the energy conversion and altering the duty cycles.

7. Acknowledgements

This study was carried out in the framework of Clean Sky 2 Joint Undertaking under the European Union's Horizon 2020 research and innovation programme. The authors wish to thank the Clean Sky 2 project to fund Integrated Intelligent Bearing Systems for UHPE Ground Test Demo (I^2BS) project.

References

[1] R. Freeland. *Energy harvesting: A practical reality for wireless sensing, In press*. 2011.

[2] J. Southcombe. *Condition monitored maintenance for rail-RSSB, In press*. Presentation. 2015.

[3] Z. Hadas, V. Vetiska, Z. Ancik, C. Ondrusek, and V. Singule. "Development of energy harvester system for avionics". In: *SPIE Microtechnologies*. International Society for Optics and Photonics. 2013, 87631F–87631F.

[4] A. Kurs, A. Karalis, R. Moffatt, J. Joannopoulos, P. Fisher, and M. Soljačić. "Wireless power transfer via strongly coupled magnetic resonances". In: *science* 317.5834 (2007), pp. 83–86.

[5] A. Karalis, J. Joannopoulos, and M. Soljačić. "Efficient wireless non-radiative mid-range energy transfer". In: *Annals of Physics* 323.1 (2008), pp. 34–48.

[6] F. Zhang, S. Hackworth, W. Fu, C. Li, Z. Mao, and M. Sun. "Relay effect of wireless power transfer using strongly coupled magnetic resonances". In: *IEEE Transactions on Magnetics* 47.5 (2011), pp. 1478–1481.

[7] D. Graham, J. Neasham, and B. Sharif. "Investigation of methods for data communication and power delivery through metals". In: *IEEE Transactions on industrial electronics* 58.10 (2011), pp. 4972–4980.

[8] P. Durand-Estèbe, V. Boitier, M. Bafleur, and J. Dilhac. "Thermoelectric Harvester to power SHM Sensors in Aircraft Pylon". In: *5èmes Journées Nationales sur la Récupération et le Stockage d'Énergie pour l'Alimentation des Microsystèmes Autonomes (JNRSE'2015)*. 2015.

[9] D. Samson, M. Kluge, T. Becker, and U. Schmid. "Wireless sensor node powered by aircraft specific thermoelectric energy harvesting". In: *Sensors and Actuators A: Physical* 172.1 (2011), pp. 240–244.

[10] F. Häggström. "Energy Harvesting for Smart-internet-connected Bearings". PhD thesis. Luleå tekniska universitet, 2015.

[11] N. White, P. Glynne-Jones, and S. Beeby. “A novel thick-film piezoelectric micro-generator”. In: *Smart Materials and Structures* 10.4 (2001), p. 850.

[12] S. Beeby and N. White. *Energy harvesting for autonomous systems*. Artech House, 2010.

[13] M. Daqaq, R. Masana, A. Erturk, and D. Quinn. “On the role of nonlinearities in vibratory energy harvesting: a critical review and discussion”. In: *Applied Mechanics Reviews* 66.4 (2014), p. 040801.

[14] A. Erturk and D. Inman. *Piezoelectric energy harvesting*. John Wiley & Sons, 2011.

[15] D. Spreemann and Y. Manoli. *Electromagnetic vibration energy harvesting devices: Architectures, design, modeling and optimization*. Vol. 35. Springer Science & Business Media, 2012.

[16] B. Zaghari, E. Rustighi, and M. Ghandchi Tehrani. “An experimentally validated parametrically excited vibration energy harvester with time-varying stiffness”. In: *SPIE Smart Structures and Materials+ Nondestructive Evaluation and Health Monitoring*. International Society for Optics and Photonics. 2015, 94390S–94390S.

[17] T. Miller. *Electronic control of switched reluctance machines*. Newnes, 2001.

[18] D. M. Rowe. *CRC handbook of thermoelectrics*. CRC press, 1995.

[19] A. Hochbaum, R. Chen, R. Delgado, W. Liang, E. Garnett, M. Najarian, A. Majumdar, and P. Yang. “Enhanced thermoelectric performance of rough silicon nanowires”. In: *Nature* 451.7175 (2008), pp. 163–167.

[20] A. Bitschi. “Modelling of thermoelectric devices for electric power generation”. PhD thesis. Technical University of Vienna, 2009.