Energy Harvesting for Aerospace Structural Health Monitoring Systems

M R Pearson, M J Eaton, R Pullin, C A Featherston and K M Holford
Cardiff School of Engineering, Cardiff University, Queen’s Buildings, The Parade, Newport Road, Cardiff, CF24 3AA
pearsonmr@cardiff.ac.uk

Abstract. Recent research into damage detection methodologies, embedded sensors, wireless data transmission and energy harvesting in aerospace environments has meant that autonomous structural health monitoring (SHM) systems are becoming a real possibility. The most promising system would utilise wireless sensor nodes that are able to make decisions on damage and communicate this wirelessly to a central base station. Although such a system shows great potential and both passive and active monitoring techniques exist for detecting damage in structures, powering such wireless sensors nodes poses a problem. Two such energy sources that could be harvested in abundance on an aircraft are vibration and thermal gradients. Piezoelectric transducers mounted to the surface of a structure can be utilised to generate power from a dynamic strain whilst thermoelectric generators (TEG) can be used to generate power from thermal gradients. This paper reports on the viability of these two energy sources for powering a wireless SHM system from vibrations ranging from 20 to 400Hz and thermal gradients up to 50°C. Investigations showed that using a single vibrational energy harvester raw power levels of up to 1mW could be generated. Further numerical modelling demonstrated that by optimising the position and orientation of the vibrational harvester greater levels of power could be achieved. However using commercial TEGs average power levels over a flight period between 5 to 30mW could be generated. Both of these energy harvesting techniques show a great potential in powering current wireless SHM systems where depending on the complexity the power requirements range from 1 to 180mW.

1. Introduction
Structural health monitoring (SHM) for aerospace applications offers a real viable solution for full coverage continuous monitoring of aircraft structures. In essence it would allow for the optimal use of the structure, drastically alter maintenance regimes and minimises downtime, whilst also improving reliability and safety. Furthermore the implementation of an SHM system at the design stage could allow for more optimised structures in safety critical areas which would reduce weight [1]. This would lead to improved aircraft performance, lower fuel consumption and greater maximum range which would reduce the running costs of an aircraft.

However for these systems to become viable it would need to consist of wireless sensor nodes that can communicate information on damage wirelessly to a central base station. One option for powering a system is to harvest energy from sources that exist in abundance in the aircraft environment, two such sources are vibration and thermal energy. Research has shown that power levels in the µW range
can be generated by piezoelectric devices and in the mW range by thermal electric generators (TEG) [2].

Piezoelectric materials can generate an AC voltage from an applied mechanical strain and hence harvest power from vibrations. Due to the high impedance nature of these devices they generate large voltage and a small current output. A cantilever piezoelectric beam with a proof mass generated 4mW for 1.53g at a resonant frequency of 5Hz for railway applications [3]. Microelectromechanical systems (MEMS) consisting of several piezoelectric cantilevers have been shown to generate 11nW at a resonant frequency of 35.8Hz and an acceleration level of 0.1g [4]. The above research has relied on a resonant devices, however in most applications the harvesters will be subjected to broad band vibrations. One way of producing broad band energy harvesters is to introduce non-linearities into the system [5]. Experimental studies of piezoceramic actuators for power generation found that MIDE Quickpak devices without interdigitated electrodes showed the greatest power output [6].

TEG generators utilise the Seebeck effect where a voltage can occur if a thermocouple consisting of two different semi-conductors is subjected to a temperature difference. Several of these thermocouples are joined together to form a TEG. Generally TEGs are lower impedance devices generate lower voltage and higher current levels. Experimental evaluation and modelling showed an average power of 50mW could be generated for temperature gradients that exist between the fuel tank and outer wing skin on an aircraft [7]. A TEG energy harvester was developed for elevated temperatures generated 40mW from a hot side temperature of 200 ºC [8] whilst a novel TEG design for aircraft applications was able to generate 20mW for a temperature gradient of 20ºC [9].

This papers reports on investigation of assessing the feasibility of both vibration and thermal energy harvesting for generating power of aerospace SHM applications.

2. Experimental Procedure and Simulation

2.1. Vibration Energy Harvesting
An investigation into the feasibility of using a piezoelectric device to provide power for a SHM system from typical aircraft vibrations was undertaken. Depending on whether the aircraft is taking off, landing or at cruising altitude vibrations occur at frequencies between 0-300Hz. The MIDE Quickpack QP10n was utilised as the harvesting device as shown in Figure 1. It consists of a rectangular sheet of piezoelectric material housed in a flexible copper clad polyimide laminate. The device was adhered using M-Bond AE-10 strain gauge adhesive manufactured by Vishay Precision group to the centre of a 300mm diameter circular disc made from aerospace grade BS1470 6082-T6 aluminium with a thickness of 0.7mm. Figure 1 shows the bespoke test rig that was developed in order to promote curvature in one direction. An LDS V201 electromagnetic shaker driven by a PA25E amplifier was placed underneath the centre of the panel. A brass connecting rod bonded to a bar was attached to the shaker in order to vibrate the panel.

![Figure 1. Experimental set-up for the energy harvesting device (a) and novel test rig (b)](image-url)
The panel was subject to a range of vibrations between 20 and 400Hz using a sinusoidal driving signal, at each particular frequency the load resistance was altered from 1MΩ to 5kΩ in order to gain the maximum power transfer. The resulting voltage traces were recorded on an oscilloscope which recorded the peak and RMS voltage.

2.2. Thermal Electric Energy Harvesting

Certain technological advances have been made in TEG development since previous work conducted at Cardiff University [7]. Micropelt have developed a series of high-tech thin film TEGs including the MPG-D751 which was selected for the investigation into the feasibility of powering an SHM system from temperature gradients that exist on an aircraft. Micropelt has also developed a simulation tool ‘mypelt’ which enables the evaluation of their devices, this generates a three dimensional function of the output voltage from the device in terms of the average temperature, \(T_m\), and the temperature gradient, \(\Delta T\).

\[
V = 0.0783\, \Delta T + 3.6097 \times 10^{-8} \, T_m \tag{1}
\]

Utilising this three dimensional function and temperature data taken from thermocouples placed at various positions on an aircraft (as seen in Figure 2) it is possible to simulate output voltage of an individual TEG. In addition by knowing the internal resistance of the TEG it is then possible to derive the power output for a particular temperature scenario, integrating the instantaneous power output and dividing by the time of the simulation gives the average power levels.

![Figure 2. Locations of thermocouples used for the TEG power output simulation](image)

3. Results and Discussion

3.1. Vibration Energy Harvesting Results and Discussion

Figure 3 shows the peak power output for a variety of input frequencies of vibrations in terms of the matched load resistance. The figure shows that for each frequency there is a peak in the power output for the device which corresponds to a particular load resistance. Also as the frequency of vibration is altered the load resistance at which the peak power is observes changes. This becomes increasingly prevalent when considering broadband nature of the frequency of vibration for aerospace applications.

Figure 4 shows the peak, RMS power and matched load resistance in order to achieve maximum power transfer and hence maximum power output. The figure shows that two narrow band peaks exist where significantly more power can be generated from the harvester. These peaks occurs at 40Hz and 300Hz where a peak power of 420 and 1100 µW and a RMS power of 220 and 440µW can be generated respectively. The peaks in power outputs are most likely due to the resonance of the device,
plate and test rig itself. The figure also shows the resistance at which the maximum power generated plateaus for increasingly frequency bands this was due to not having the resolution in terms of resistance values to which the power levels were measured. However the figure does show the decrease in load resistance from 200kΩ to 5kΩ. As previous stated in order to maximise power transfer the load resistance needs to match the internal resistance of the device. If the internal resistance changes for increasing frequencies and the load is constant this can lead to inefficient transfer.

![Figure 3](image)

**Figure 3. Peak power output from QP10n device for a variety of frequencies and load resistance**

![Figure 4](image)

**Figure 4. Peak Power (a) and RMS power (b) for the QP10n device in terms of the matched load resistance for different frequency of vibrations**

3.2. Thermoelectric Energy Harvesting Results and Discussion

A comparison of the power output for an individual MPG-D751 module utilising the ‘mypelt’ simulation tool for various different locations on an aircraft was undertaken. Figure 5 shows example results for the temperature profiles for two hydraulics pipelines on an aircraft. The figure shows that there is a fairly constant temperature differential of around 10°C with a maximum of 20°C. This is advantageous because the temperature profiles remain relatively constant throughout the flight therefore not reaching equilibrium between the two where no further heat transfer would occur. Also due to the close proximity of these two lines to one another it would be relatively easy to mount the TEG between the two pipelines. Figure 6 shows the corresponding voltage and power levels of the TEG for that particular temperature gradient and shows a peak power of 8mW is generated at a voltage of 1.75V. Table 1 shows the resulting investigation for various different locations on an
aircraft. It shows the peak temperature differential, peak power and average power over the duration of each particular flight. It shows a peak power 34.15mW can be generate by a single TEG for a temperature gradient of 40°C resulting with an average power 22.58mW. These TEGs can also be arranged in series or parallel or a combination of the both in order to the increase the power output, however careful consideration of the weight and cost of the energy harvesting system is necessary.

When comparing the power outputs from both vibrational and thermoelectric energy harvesting it has been showed that the QP10n generates power in the μW range while a TEG can generate power in the mW range. This investigation has shown that both types of harvesting are feasible for powering an SHM system where depending on the complexity the power levels can vary between 1-180mW.

| Cargo skin | Temperature Differential, °C | Peak Power, mW | Average Power, mW |
|------------|-----------------------------|----------------|--------------------|
| Cargo Primary Insulation | 40 | 34.15 | 22.58 |
| Hydraulic Pipeline 1 | 20 | 7.97 | 3.07 |
| Hydraulic Pipeline 2 | | | |
| Waste water tank | 15 | 5.46 | 2.99 |
| Waste water ambient | | | |
| E-bay fuselage skin | 35 | 18.72 | 6.42 |
| E-bay primary insulation | | | |
| Cabin wall fuselage skin | 30 | 13.36 | 3.97 |
| Cabin wall primary insulation | | | |
| Cabin wall fuselage skin | 40 | 30.06 | 11.70 |
| Cabin wall secondary insulation | | | |

4. Conclusions
A novel test rig was developed in order to evaluate MIDE Quickpack device for the use of harvesting power from ambient vibrations on an aircraft. Experimental results showed that peak power levels from 1-1000μW and RMS power level of 0.5-400 μW could be generated. The power levels were highly dependent on the frequency and internal resistance of the device.
A numerical analysis was undertaken utilising the ‘mypelt’ simulation tool to determine the power output for an individual Micropelt MPG-D751 TEG for various different locations on an aircraft. Peak power levels ranging from 5.46-30.06mW and average power levels between 2.99-11.70mW were simulated from the temperature data. However careful considerations of the assumptions of the simulation are necessary firstly the analysis assumed a matched load resistance in order to achieve maximum power transfer, in reality it may not be possible to physically harvest from some of these locations and it might also not be possible to achieve the specified temperature gradient across the TEG module.

Both energy harvestings techniques shows a real potential for powering an SHM system, however in reality these devices would not be able to directly power a SHM system due to the varying nature of the sources. Therefore a further power management system would be necessary in order to provide a stable power source from the dynamic nature of the energy sources in order to power an SHM system.

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