30th Eurosensors Conference, EUROSENSORS 2016

Strain Energy Harvesting Powered Wireless Sensor Node for Aircraft Structural Health Monitoring

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Abstract

This paper presents a wireless sensor node (WSN) powered by a strain energy harvester (SEH) through an adaptive power management module (PMM) for aircraft structural health monitoring (SHM). The energy distribution in the system, the efficiencies of the whole systems, and the WSN powering capability of the SEH under different strain loadings were studied to understand the developed system performance for practical applications of an autonomous WSN. Experimental results show that the SEH is able to produce up to 3.34 mW under strain loading of 600 με at 10 Hz. The WSN can be powered up through the adaptive PMM at efficiency from 70 to 80 % under different test conditions.

Keywords: piezoelectric; power management; strain energy harvester; structural health monitoring

1. Introduction

Traditionally, aircrafts are manually inspected on ground based on a fixed schedule. Such approach is very labor intensive and time consuming. An alternative to this schedule-based maintenance is conditional maintenance based on the structural condition of the aircraft using a SHM system installed in the aircraft and to carry out the maintenance when a fault is detected [1]. However, conventional SHM systems are wired systems where these cables inadvertently add extra weight to the aircraft. This will increase the fuel consumption and operational cost of

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the aircraft. A natural solution to this problem is the integration of wireless sensing and communication technologies in the form of WSN.

As WSNs need a local power, batteries are not permitted in most aircraft structures and thus energy harvesting is an area which has been widely investigated to provide long lasting energy to WSNs which are usually powered by batteries. Therefore, aircraft SHM using energy autonomous WSNs has many advantages over wired systems, battery powered WSNs or on ground manual inspection in terms of the cost, time, maintenance, and installation in addition to the reduced weight of wires. Study of the capability of a SEH to generate power from the dynamic deformation of an aircraft wing shows that it is feasible to power up a WSN from that amount of strain energy generated [2]. However, there is a lack of studies which includes the PMM and WSN to determine the actual operation of a SEH powered WSN. In this paper, a thorough study which integrates a SEH, an adaptive PMM, an energy aware interface (EAI) and a WSN as a SHM system is presented. The developed system has addressed the mismatches between the SEH and the WSN in terms of energy and electrical loading.

2. Strain energy harvester powered wireless sensor node

2.1. Strain energy harvester

There will be some vibrations when an aircraft is taking off, cruising, and landing. The vibration causes some bending to different parts of the aircraft. The bending moment will slightly stretch the skin of the aircraft and this strain experienced by the skin of aircraft can be converted into electrical energy. Therefore, a macro-fiber composite (MFC) M8528-P2 was used as the SEH by bonding it onto a carbon fiber composite material which emulates a small section of the skin of an aircraft as shown in Fig. 1(a). An Instron dynamic testing machine was used to apply different strain loadings at different frequencies onto the composite material. Both ends of the composite material which will be gripped by the Instron dynamic testing machine were reinforced with two pairs of aluminum plates.

2.2. Developed system

Fig. 1(b) shows the block diagram of the developed system which is composed of five main parts: (1) a full wave bridge (FB) rectifier for converting the AC voltage produced by the SEH into DC voltage, (2) an adaptive PMM for maximum power point (MPP) finding and regulate the rectified DC voltage to a 3.3 V DC voltage which is usable by low power electronics, (3) a storage capacitor C_S for energy accumulation, (4) an EAI for energy flow control between the storage capacitor and the WSN, and (5) a WSN for sensing tasks. The adaptive PMM is able to harvest energy at high efficiency near the maximum power point of the SEH regardless of the strain level applied onto the SEH and the operation modes of the WSN [3]. This attribute is essential because the ambient environment is highly variable, which causes the SEH to produce different energy outputs. The WSN can also be seen as a dynamic load during different operation modes because it draws different amount of current.

3. Experimental verification

Experiments will be used to determine the power produced by the SEH, the energy distribution in the developed system, and the WSN powering capability of the SEH through the developed system. Fig. 2(a) shows the developed system on a piece of printed circuit board (PCB) which consists of a temperature sensor and a humidity sensor to monitor the environmental condition and an accelerometer to measure vibration. A 10 mF supercapacitor is used as
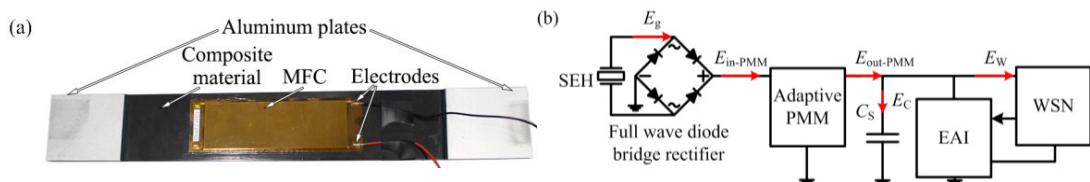

Fig. 1. (a) Fabricated SEH by bonding an MFC on a piece of composite material; (b) Block diagram of the developed system with energy flow.

the energy storage device. Cyclic peak-to-peak strain loading of 600 µε with frequency of 2, 4, 6, 8, and 10 Hz was applied onto the composite material by using Instron dynamic testing machine as shown in Fig. 2(b). The test was also repeated using different strain loadings of 300 µε, 400 µε, and 500 µε at 10 Hz. Energy generated by the SEH E_g, energy flowing into the PMM E_{in-PMM}, energy output from the PMM $E_{out-PMM}$, energy in the storage capacitor E_C, and energy consumed by the WSN E_W are measured to determine the efficiency of the system.

4. Results and discussions

Power generated by the SEH under different strain loadings and frequencies is shown in Fig. 3(a). The SEH can generate milliwatts of power from strain loadings between 300 and 600 µε which are sufficient to power up the developed energy harvesting powered WSN on PCB. By taking the test condition at 600 µε and 10 Hz as example, energy distribution in the system is shown in Fig. 3(b). The rectifier is fairly efficient as energy E_g generated from the SEH and E_{in-PMM} have very little difference. The PMM consumes around 25 % of the energy and is able to transfer the energy effectively into the storage capacitor as $E_{out-PMM}$ and E_C overlap with each other before the WSN starts consuming energy. Detailed efficiencies of the system at different test conditions are given in Table 1.

The WSN can be powered up by the SEH in all the tests. Fig. 4 shows the voltage and current profiles of the WSN and the storage capacitor when strain loading of 600 µε at 10 Hz was applied onto the SEH as an example. The EAI releases the energy from the storage capacitor once it reaches 3.16 V and stops the energy flow at 2.55 V. When the capacitor was charged from 0 to 3.16 V for the first time, this period of time is known as the cold start (CS) time t_c for the WSN. The WSN then becomes active (A) to do the sensing and data transmission and goes back to sleep (S) mode when the voltage drops to 2.55 V. This allows the capacitor to be recharged to 3.16 V to do the next transmission again in a shorter time, which is also known as warm start time t_w. The cycles repeat as long as strain energy is available. Detailed cold start time, active time, and warm start time is given in Table 1. Since most of the energy was supplied by the storage capacitor when the WSN became active, t_a is about the same in all the
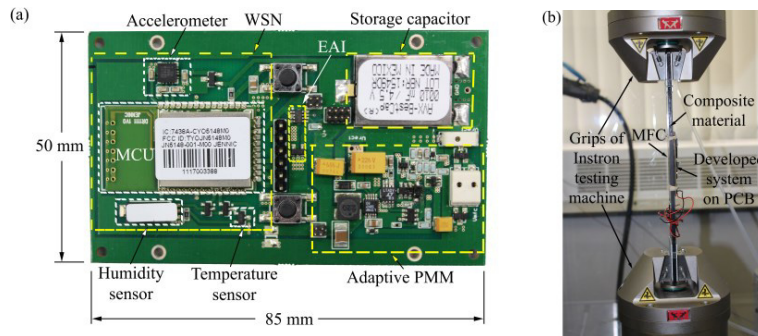

Fig. 2. (a) Developed system on a PCB; (b) Experimental setup using Instron testing machine to apply dynamic strain loadings onto the SEH.
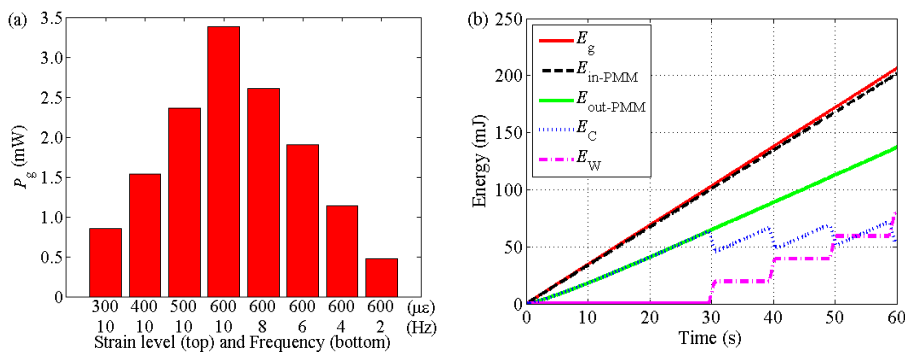

Fig. 3. (a) Power generated by the SEH under different strain loadings and frequencies; (b) Energy distribution in the developed system.

tests because the size of capacitor is fixed. The difference is due to the PMM is still transferring energy from the SEH to its output, which prolongs t_a especially when P_g is high. However, with different amount of power generated by the SEH due to different strain loadings or frequencies, the time required to charge up the capacitor varies.
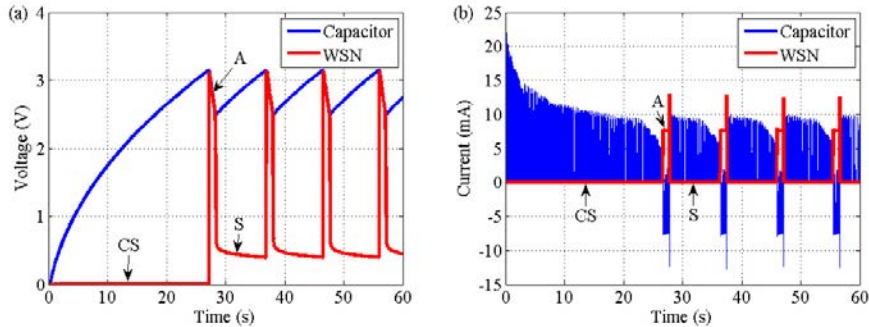

Fig. 4. (a) Voltage profiles and (b) current profiles of the capacitor and WSN.

Table 1. Performance of the developed system.

Test condition	$E_{\text{out-PMM}}/E_g \times 100$ %	t_c (s)	t_w (s)	t_a (s)
300 µε at 10 Hz	80	95.47	29.18	0.95
400 µε at 10 Hz	72	54.04	16.06	0.91
500 µε at 10 Hz	71	36.84	12.45	1.09
600 µε at 10 Hz	75	26.69	8.65	1.08
600 µε at 8 Hz	79	31.91	10.72	1.09
600 µε at 6 Hz	74	43.40	13.13	0.92
600 µε at 4 Hz	76	71.69	22.74	0.91
600 µε at 2 Hz	73	179.56	57.41	0.89

5. Conclusion

A fully energy autonomous WSN for aircraft SHM powered by a SEH is presented. The implemented system shows high performance in terms of adaptability and energy transfer efficiency at 70 to 80 %. The WSN can be successfully turned on to perform the programmed task under all the test conditions. The capacitor can be charged up within a short period of time and provide sufficient energy for the WSN to stay active for about 1 second. The long active time enables the WSN to take dynamic measurement which is one of the essential measurands for SHM. Therefore, the developed system is potentially deployable for real-world SHM applications.

Acknowledgements

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