A SELF POWERED TAG FOR WIRELESS STRUCTURE HEALTH MONITORING IN AERONAUTICAL APPLICATIONS

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Abstract: This paper reports a self powered smart tag consisting of a vibration energy harvester, the power conditioning circuit, sensors and a RF transmitter for wireless structural health monitoring (SHM) in aeronautical applications. The smart tag has dimensions similar to a credit card and aims to be integrated into the surface of the aircraft. The smart tag is powered by an integrated bimorph piezoelectric generator that extracts energy from ambient vibrations at the frequency of 67Hz and the amplitude of 0.4g (3.9ms^{-2}). The generator is fabricated using thick film printing technology. Experimentally, the generator produced the maximum RMS output power of 181μW which is sufficient to enable periodic sensing and transmission. Description of the smart tag as well as the experimental results of the piezoelectric generator are presented.

Keywords: Vibration Energy Harvesting, Wireless Sensing, Structure Health Monitoring

INTRODUCTION

Health and usage monitoring systems (HUMS) have been in use for nearly 30 years predominantly in helicopters but more recently they are being introduced to fixed wing aircraft. HUMS work by monitoring, for example, engine and gearbox performance by collecting and analysing data from a range of sensors. The system should also enable the communication and storage of the data. In addition to early warning of system failures during flight, the analysed data allows operators to identify component and system usage in order to provide effective maintenance schedules [1]. This work is performed as part of an EC framework 7 research project TRIADE which is concerned with the development of structural HUMS for aeronautical applications.

The aim of the TRIADE project is to develop a low-profile, planar, self powered intelligent sensor device (also known as smart tag) that can be fabricated within a composite material and thereby embedded in the structure of an aircraft to monitor structural health and transmit measurement data wirelessly to the base station during the flight. Considering the environment during the flight, vibration energy harvesting is thought to be the best solution to powering the smart tag.

Vibration energy harvesting has been studied comprehensively over the past decades. Piezoelectric, electromagnetic, electrostatic and magnetostrictive transduction mechanisms are commonly used to convert mechanical energy into electrical energy [2]. Due to the specific size restriction in this application, a thick film piezoelectric generator is selected as the power source. An initial prototype of the thick film piezoelectric generator designed for this application has been reported [3][4]. The generator produced a peak power of 117μW at 6.9 ms^{-2} and 70Hz with an optimum load of 140kΩ and an output voltage of 2.9V.

In this paper, a credit card sized self powered smart tag consisting of a piezoelectric vibration energy harvester, the power conditioning circuit, sensors and a RF transmitter is introduced. An improved bimorph piezoelectric generator has been built to suit the target vibration with the frequency of 67Hz and the peak amplitude of 0.4g (3.9m·s^{-2}) and the experimental results of the generator will be presented together with the power conditioning solution.

SMART TAG
Overview

The smart tag has dimensions similar to a credit card, i.e. $85 \times 55 \times 3$mm (Fig. 1).
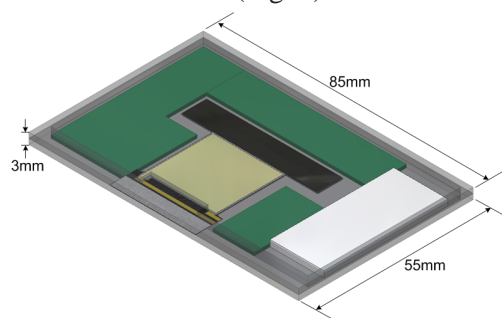

Fig. 1: Perspective view of the smart tag.

It consists of three layers as shown in Fig. 2. The lid and base layers provide protection for the smart tag, rigid clamping for the generator and contain etched recesses that provide the space for the generator to work. Additionally, the base layer is used to mount a super capacitor for energy storage and the

electronic circuit for power management, sensors and an RF transmitter. The piezoelectric generator is located in the middle layer which also contains spaces for the electronics and super capacitor.
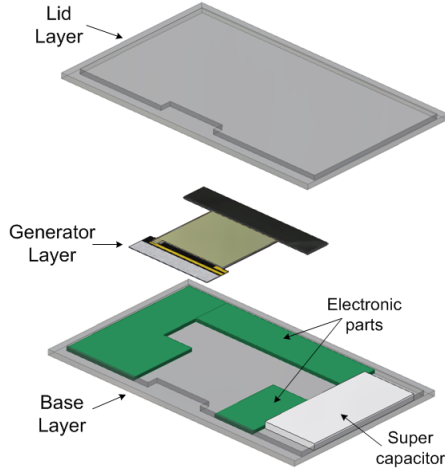

Fig. 2: Integration concept of the smart tag: lamination of different layers.

The smart tag is divided into five areas as shown in Fig. 3. The piezoelectric generator is located in the centre of the tag and a super capacitor is placed at the edge of the tag for power storage. Three PCB boards are distributed in the remaining space for (a) power conditioning electronics, (b) sensors and (c) the microcontroller with RF components.
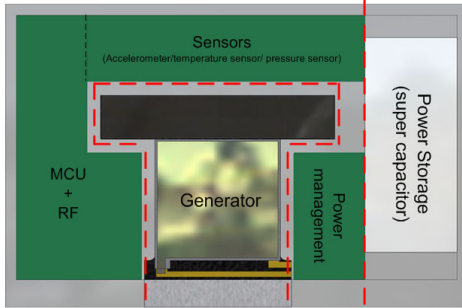

Fig. 3: Layout of the smart tag.

System Description

Fig. 4 shows the flow diagram of the system of the smart tag. The AC voltage generated by the piezoelectric generator is first rectified by a bridge rectifier. P-SPICE simulation shows that schottky diode BAT 754 is the best suitable for this application and it has a low voltage drop of only 0.2V. A super capacitor is charged by the rectified DC signal. Due to the limitation of the thickness of the smart tag, planar super capacitors from Cap-XX are chosen to be the power storage device. A super capacitor of 0.55F and 4.5V voltage capacity is selected to provide an acceptable charging time.
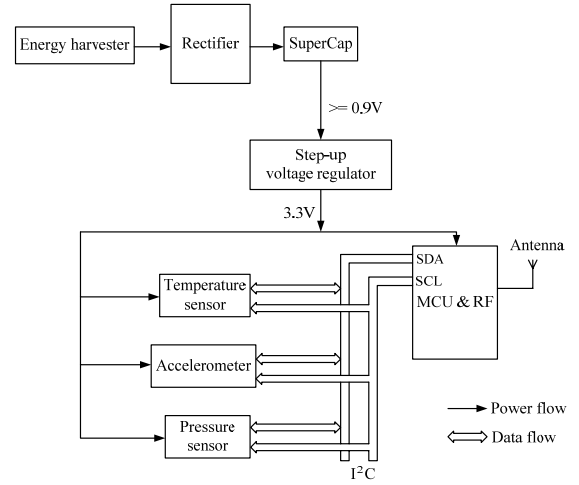

Fig. 4: System flow diagram.

To make the best use of the power generated by the energy harvester, a step-up voltage regulator, TPS61097 from Texas Instruments, is used. It is able to step up the input voltage from as low as 0.9V to a constant output voltage of 3.3V which is capable of powering most ICs available on the market. Furthermore, it has efficiency up to 95% and a typical quiescent current of less than 5 µA, which makes the system power efficient.

Low power microcontroller CC2430 from Texas Instruments (TI) is selected as the microcontroller and RF solution. CC2430 integrates an 8051 core CPU and a RF transceiver which is compatible with 2.4 GHz IEEE 802.15.4 and ZigBee protocols. Wireless sensor networks of smart tags can be easily built based on CC2430. Typically, it has a current consumption of 26.9mA when the transceiver is active.

The microcontroller communicates with the sensors via the I²C bus. The temperature sensor, TMP 112 from TI, the 3-axis accelerometer, ADXL 345 from Analog Devices and the pressure sensor, MPL115A2 from Freescale Semiconductor can all operate at 3.3V and have the current consumption of 15µA, 40µA and 5µA, respectively.

PIEZOELECTRIC GENERATOR
Theory

A linear model of cantilever-based bimorph piezoelectric generator was introduced by Roundy [5] as:

$$\ddot{z} + 2\zeta_m \omega_n \dot{z} + \omega_n^2 z - \frac{d_{31}\omega_n^2}{t_{pzt}} \cdot v = b^* \cdot a \quad (1)$$

$$R_L C_p \dot{v} + v + m R_L \frac{d_{31}\omega_n^2}{t_{pzt}} \dot{z} = 0 \quad (2)$$

where z is the displacement of the inertial mass, m, the damping factor is given by ζ_m, t_{pzt} is the thickness of the PZT layer, b^* is the ratio of strain to vertical displacement, a is the acceleration, R_L is the load resistance, C_p is the capacitance of the PZT layer and v is the voltage across the electrodes.

For nonlinear generators, the model can be obtained by combining the Duffing equation with linear piezoelectric generator model in Eq. 1 as:

$$\ddot{z} + 2\zeta_m\omega_n\dot{z} + \omega_n^2 z + \alpha z^3 - \frac{d_{31}\omega_n^2}{t_{pzt}}\cdot v = b^*\cdot a \quad (3)$$

where α is the nonlinear spring factor. α is positive in the case of a hard spring effect and negative in the case of the soft spring effect. Details of the nonlinear model can be found in [4].

T-shape Generator

Due to limitations on the thickness of the smart tag, the maximum tip displacement of the generator is 1mm. As an improvement to a previous generator [3], a T-shape cantilever (Fig. 5) is used to replace the conventional cantilever.
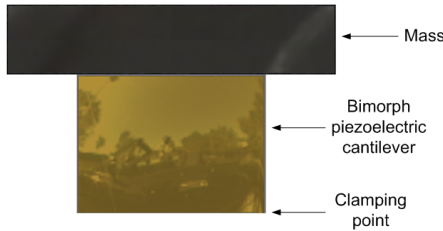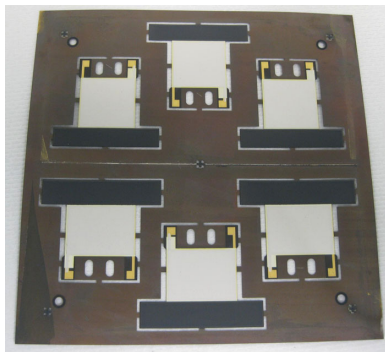

Fig. 5: T-shape piezoelectric generator.

Fig. 6: Screen printed T-shape piezoelectric generator.

A T-shape cantilever condenses the proof mass along the direction of the width of the cantilever rather than the direction of the span of the cantilever so that the tip displacement can be reduced to meet the power requirement within the size constraints.

The generator is fabricated using screen printing technology. A high density printable paste was used to form the inertial mass so that the devices are able to

be fabricated completely using the screen printing process [3]. Fig. 6 shows the finished printed T-shape piezoelectric generators.

Experimental results

The generator aims to work at the resonant frequency of 67Hz and the peak vibration amplitude is $0.4\textbf{\textit{g}}$ (3.9ms^{-2}), i.e. $0.29\textbf{\textit{g}}_{RMS}$ (2.8ms^{-2}), which coincides with the peak vibration taken from a helicopter during flight [3]..

Fig. 7 shows the experimental results of the RMS output power at the optimum load resistance of 34kΩ when the two PZT layers were connected in parallel. It was found that the generator managed to produce the maximum RMS output power of 181μW at the resonant frequency of 63.1Hz. Compared to previously reported generator [3], an increase of 55% in output power is achieved at a 60% lower excitation.
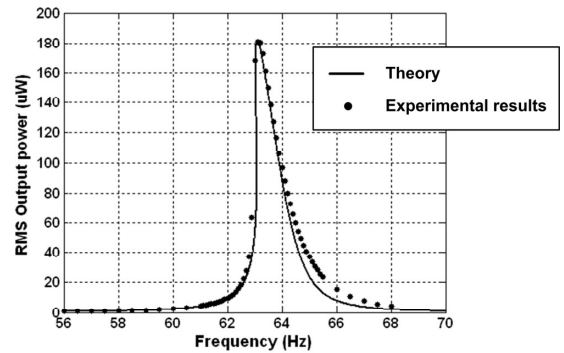

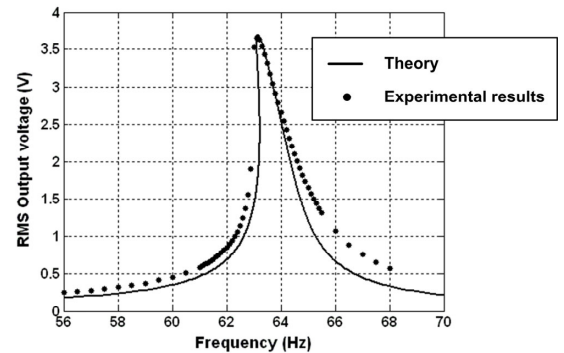
Fig. 7: Output power of the piezoelectric generator.

Fig. 8: Output voltage of the piezoelectric generator.

Fig. 8 shows the open circuit RMS output voltage of the generator. The maximum open circuit RMS output voltage is 3.65V, which is therefore the maximum voltage to which the super capacitor can be charged. The generator demonstrated soft non-linearity in the test and the nonlinear spring factor was found to be -1.5×10^{10}m^{-2}s^{-2} according to the non-linear model presented in [4].

The voltage across the super capacitor when being charged by the piezoelectric generator via a bridge rectifier is shown in Fig. 9. It takes about 3.9 hours to

charge the super capacitor from 0V to 0.9V when the sensing system is able to start working.
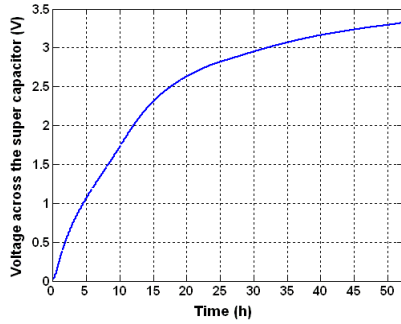

Fig. 9: Voltage across the super capacitor when being charged by the piezoelectric generator.

DUTY CYCLE

One of the most important characteristics of a self-powered system is its duty cycle which is defined as the period in which the system accumulates enough energy to perform one sensing and wireless data transmission (termed 'one performance').

The total current consumption of the proposed system is about 27mA. Given the supply voltage of 3.3V, the total power consumption of the system is 89.1mW. The duty cycle depends on the duration that the system is active, τ and the initial voltage across the super capacitor when the system is activated, V_1. The energy consumed in one performance, E_T, is given by:

$$E_T = 0.0891\tau = \eta_r \left(E_{c1} - E_{c0} \right) = \eta_r \left(\frac{1}{2}CV_1^2 - \frac{1}{2}CV_0^2 \right)$$

$$(4)$$

where E_{c1} and E_{c0} are the energy stored in the super capacitor before and after one performance, respectively and V_0 is the voltage across the super capacitor after one performance is finished. C is the capacitance of the super capacitor, 0.55F in this case. η_r is the efficiency of the step-up voltage regulator, i.e. 95% in this case.

Rearranging Eq. 4 gives expression of the voltage across the super capacitor before the system is activated as:

$$V_1 = \left(\frac{0.0891\tau \cdot 2}{\eta_r \cdot C} + V_0^2 \right)^{\frac{1}{2}}$$

$$(5)$$

Combining Eq. 5 with the charging plot as shown in Fig. 9 gives the duty cycle of the system against τ and V_0 as shown in Fig. 10. It is found that the shorter the time that the system is active, the shorter the duty cycle. Fig. 10 also demonstrates that the system has the minimum duty cycle when the voltage across the super capacitor is around 1.9V.
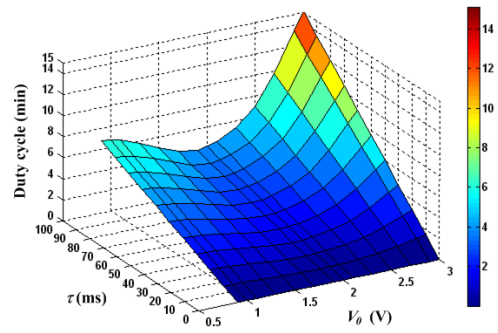

Fig. 10: Estimated duty cycle of the system.

CONCLUSION

This paper highlights the development of a self-powered low-profile wireless sensing device (smart tag) for structural health monitoring (SHM) in aeronautical applications. An improved thick film bimorph piezoelectric generator has been developed as the power source for the smart tag. The resonant frequency of the generator is slightly different from the target frequency. The fabrication process needs to be optimized to correct the error. The duty cycle of the sensing system has also been estimated and was found to be reasonable. More work will be done to optimize the system to minimize the total power consumption.

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