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A 120°C 20G-compliant vibration energy harvester for aeronautic environments

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Abstract. This paper reports the design, fabrication and testing of a piezoelectric energy harvester operating at 90°C and withstanding 120°C and 20G of acceleration. This harvester, along with its dedicated power management circuit, has been designed to supply a 3-channel Acceleration Measurement System (AMS) for the structural health monitoring of an aircraft engine. This aeronautic-compliant bimorph harvester outputs 6.83mW at 1G, up to 246mW at 8G of acceleration and exhibits a maximum Normalized Power Density of 15.3kg.s.m⁻³ at 90°C.

1. Introduction

Autonomous wireless sensors nodes operating in harsh environments, especially at high temperatures, are of particular interest for aerospace and aeronautic sectors particularly. Indeed, Structural Health Monitoring (SHM) at various locations of an aircraft engine may help identifying and estimating structural faults or ageing phenomena (e.g. bearings). But some locations on/inside the engine can be very difficult to monitor, either because of their accessibility or because their temperatures are too high for a battery to operate. Particularly at small-scale, vibration energy harvesting has revealed a great innovation potential to supply wireless sensors nodes in such harsh environments. In this work, we use the piezoelectric principle to convert the engine's vibrations into electricity in order to supply a 3-channel Acceleration Measurement System (AMS) used to monitor the vibration level of the engine.

The performance of piezoelectric vibration energy harvesters have already been studied as a function of temperature for MEMS and macro scale devices and for various piezoelectric materials [1,2]. In this work, we present the design, from a system point of view, of a cm-scale energy harvester and its dedicated power management circuit operating in moderately-harsh environments (<120°C).

2. Design and fabrication of the harvester and its power management electronics

2.1. Vibration energy harvester

Our harvester is based on a piezoelectric bimorph cantilever (figure 1) tuned on a constant engine rotation frequency (≈ 70000 rpm, 1167Hz). A 2-degree-of-freedom (2-DOF) analytical model was used to design the harvester. It enabled to optimize the dimensions (piezoelectric and substrate thicknesses and lengths) to reach the best global electromechanical coupling while respecting the constraints of our application (resonant frequency, volume, output power, 20G acceleration).

We used Finite Element Methods (FEM) simulation in 3D (COMSOL) on the best geometry to check the validity of our optimization. We made some slight adjustments to tune the resonant frequency to 1167Hz at 90°C and to limit the maximum stress to 10MPa at 20G, i.e. far below the depolarization stress of the piezoelectric material. A tuning screw was added at the end of the beam to easily tune the resonant frequency after the assembly. If the resonant frequency is too high, the screw shifts the center of gravity of the mass to decrease the frequency. A carter surrounds the active part (the beam) to protect the harvester from unexpected shocks which may occur during the installation.

The final prototype was fabricated with an electrical discharge machining (EDM) process and dimensional controls were performed after its fabrication. A photograph of the device is shown in figure 2. A non-conductive epoxy (EPO-TEK 353ND) was used to glue the piezoelectric patches to the substrate and conductive spacers (60µm) enable the electrical contact between these two elements.

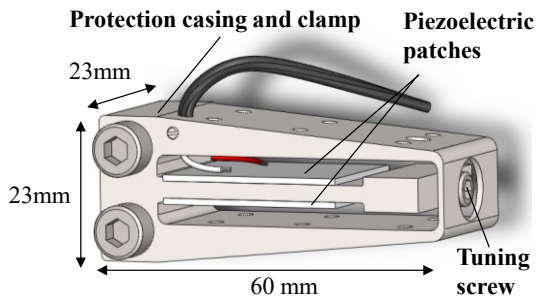


Figure 1. 3D schematic of the harvester with its dimensions.



Figure 2. Photograph of the assembled harvester.

The key dimensions of the harvester, its tolerances and the chosen materials are listed in table 1.

Table 1. Key dimensions, tolerances and materials of the piezoelectric harvester.

Parameter	Value	Tolerance
Piezo thickness	1 mm	+/-0.01mm
Piezo length	30 mm	+/-0.01 mm
Beam thickness	2.7 mm	+/-0.01 mm
Beam length	36 mm	+/-0.02 mm
Beam width	22 mm	+/-0.02 mm
Mass length	9.5 mm	+/-0.02 mm
Mass height	5.5 mm	+/-0.02 mm
Piezo material	NCE51 Noliac (PZT-5)	
Substrate material	XC75 steel	

We performed an identification of the harvester parameters by using optimization methods to get the best match between the harvester admittance (measurements) and its theoretical model [3]. The device exhibits a squared electromechanical coupling coefficient k^2 around 4.1%. Its modified coupling coefficient k_m^2 is around 4.3% and its mechanical quality factor Q_m is around 33.

2.2. Power management electronics

A dedicated power management circuit (PMC) has been designed and fabricated (figure 3). This battery-less circuit, uses capacitors as storage elements and a two-path architecture [4,5] to operate. During the cold start, a “non-optimized path” fills the capacitor C_{start} by the mean of a normally-on MOSFET K_d . When C_{start} has reached an acceptable voltage value, the harvester is then discharged through an “optimized path”, by applying a Unipolar Synchronous Electric Charge Extraction (USECE) technique [6] which fills the capacitor C_{buff} through a Flyback topology. This technique takes advantage of the MOSFET body diode (at the primary) which plays a quasi-similar role to diode half-wave shunt rectifiers. In this way, the piezoelectric element is discharged only once per mechanical period. For device having large $k_m^2 Q_m$ excited at resonance, this strategy yields higher power delivered by the

piezoelectric generator compared to the classical SECE. Finally, so as not to overdamp the mechanical system at resonance, our circuit implements a tunable SECE, extensively described in [7] : when the piezoelectric voltage reaches a maximum value, the energy stored in the piezoelectric capacitor is not entirely transferred to the primary inductor L_p . This technique is relevant when the factor $k_m^2 Q_m$ is greater than $\pi/4$, which is our case ($k_m^2 Q_m=1.42$). The control parameter β of the tunable SECE technique has been empirically set to about 25%, which means that the piezoelectric element is discharged from its maximum voltage V_{max} to $\beta \cdot V_{max}$.

As depicted in figure 3, the “Power Management” block controls the LDO which supplies the WSN. A “Discharge disable” block may disable the optimized mode when V_{buff} reaches a too high value, i.e. when the WSN’s consumption becomes lower than the harvested power.

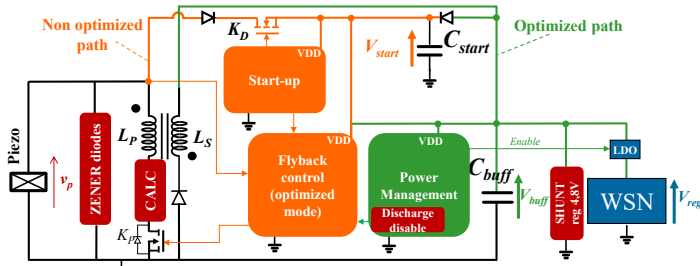


Figure 3. Schematic of the power management circuit showing the optimized and non-optimized paths.

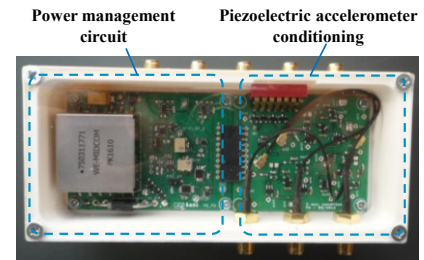


Figure 4. Photograph of the whole electronic circuit.

3. Measurement results and ageing tests of the vibration harvester

Tests were performed in a vibration chamber for various acceleration values at 90°C. As depicted in figure 5, the harvester exhibits the following power performances: 6.8mW@1G, 36.1mW@3G, 70.7mW@5G and 135mW@8G when excited at the engine frequency (1167Hz). The WSN (a 3-channel AMS) which consumes around 40mW, can be powered from 3.5G of acceleration when the aircraft engine is in steady state operation ($f_{rotation} = 1167\text{Hz}$, $T < 90^\circ\text{C}$). One can notice that the resonant frequency decreases when increasing the base acceleration. It is probably caused by the nonlinear elastic properties of the soft piezoelectric materials used in the harvester [8].

The output powers at each resonance are 6.83mW@1G, 45.9mW@3G, 112mW@5G and 246mW@8G. It corresponds to a maximum Normalized Power Density (NPD) of 15.3 kg.s.m⁻³ which is a good result at 90°C and for a highly constrained design (120°C and 20G compliant). The NPD is the ratio $P_{max}/(A^2 \cdot V)$, where P_{max} is the maximum harvested power, A the input acceleration [m.s⁻²] and V the volume of the beam [m³].

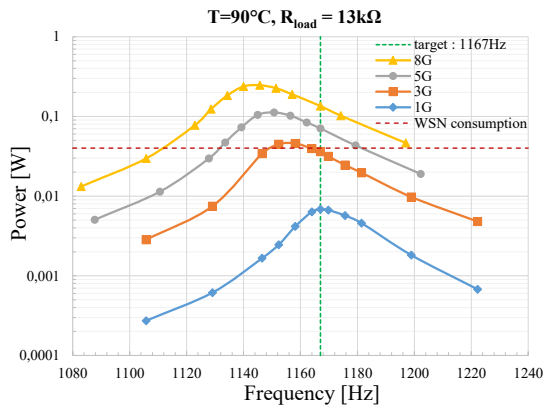


Figure 5. Electrical power as a function of the input frequency on an optimal resistive load for various acceleration values at 90°C.

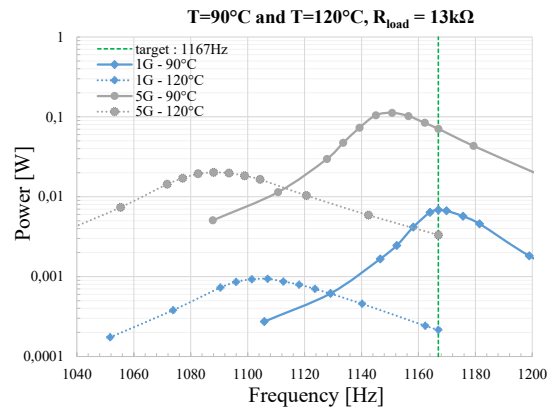


Figure 6. Electrical power as a function of the input frequency on an optimal resistive load for various acceleration values at 90°C and 120°C.

Two ageing tests at 20G were also performed at 90°C and then at 120°C: the harvester was excited for 10^7 cycles (2h) on its first resonant mode. The frequency of this mode at 90°C dropped by 3% after the first ageing, 1% after the second one and stabilized after a third ageing (120°C, 2h). For each acceleration value, the maximum power value is constant from 27°C to 90°C whereas it strongly decreases (-85%) from 90°C to 120°C at resonance (figure 6), due to the reduction of both the piezoelectric coefficients and the mechanical quality factor of the structure. From 90°C to 120°C, the resonant frequency of the harvester drops by around 5.5%.

4. Operation of the complete autonomous system in real environment

Finally, we validated the operation of the complete system (harvester, PMC, AMS) which was successfully tested on a real engine's bench where acceleration measurements of 3 aeronautic-compliant accelerometers were performed autonomously (figure 7). To the best of our knowledge, this autonomous system is the first one in prior art implementing a high acceleration (20G) and temperature (120°C) compliant piezoelectric harvester tested and validated in real conditions.

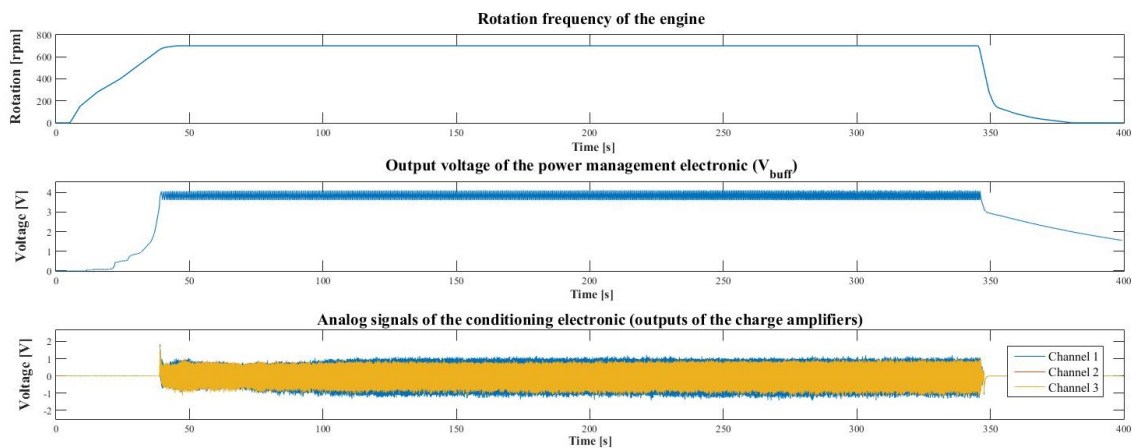


Figure 7. Autonomous measurements in real conditions: rotation frequency of the engine, output voltage of the power management electronic and the conditioning stage (prop. to the acceleration).

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