VIBRATION ENERGY HARVESTING IN AIRCRAFT USING PIEZOELECTRIC ACTUATORS

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Abstract:
In the aircraft vehicle, a part of the produced energy is transformed into mechanical vibration energy losses. This rule is more than ever true when the need for electrical energy is a crucial problem. So, systems which are able to transform the mechanical energy in a scavenged electrical energy are very interesting. The use of the very high energy density and electroelastic coupling of smart materials as piezoelectric ceramics makes it possible to achieve Vibrational Electric Energy Harvesting to weight and size ratios higher than those of conventional generators. The Amplified Piezoelectric Actuator (APA) integrating a mechanical amplifier can be interesting where the efficiency of the standard actuators is poor. In this paper, the electrical harvesting characteristics of the APA actuator in a proof mass configuration is studied. A comparison between the standard high efficiency AC/DC reclamation techniques coupled with this actuator is studied allowed to work in large voltage level variations of excitation. Experimental results show that the employment of the APA with high efficiency AC/DC converter increases the harvested power by 100% with a harvesting power up to 50 mW with only an vibrating excitation of 35 µm at its base.

Keywords: Amplified Piezoelectric Actuator , vibration energy harvesting, AC-DC conversion, electronically controllable impedance, efficiency, self powered unit.

Introduction

This paper presents the possibilities to use the Cedrat Technologies‘ Amplified Piezoelectric Actuator [1] based on multi-layer ceramics and a simple energy harvester circuit to extract the environmental vibration energy. The need in wireless and self-powered devices in a lot of applications is very important because the hardwiring with large number of sensors is expensive and time consuming. With the new low power components, the possibility of powering the sensor by scavenging ambient energy from the environment, eliminates the need for batteries and extending the lifetime indefinitely. The aircraft domain doesn't dodge in this principle and is a good application of the vibration energy harvesting because of the very high level of mechanical vibration inside the structures. In parallel, the piezoelectric device is a good candidate for the harvesting component due to its small size and high energy density. The previous approaches to harvesting energy with a piezoelectric devices [2], using piezoelectric patches showed a poor efficiency due to the electromechanical aspects of the mechanical design. The use of the Amplified Piezoelectric actuator can remedy to this problem and can provide a good solution in term of energy reclamation component. In addition, the APA is able to support high external vibrations, as checked during space qualifications [3]. Connected to different circuits to realise the AC-DC conversion, the feasibility of using a APA actuator in a proof mass configuration as a source for energy reclamation is investigated and a design including all these functions is realised to compare the simulations and the experimentation on a tests bench: A direct charge method through a rectifier bridge and a rectifier bridge coupled with a impedance converter which can adapt the load via the duty cycle of the switching converter. The results show the capabilities of the whole to harvest a maximum of energy up to 48% from the input vibration. To apply these results, a demonstrator using the previous electronic functions coupled with the electromechanical device is realised to supply a AM transmitter and its electronics.

Electromechanical model of the piezoelectric device

The base of the electromechanical converter is the APA400M-MD from Cedrat Technologies. This actuator presents a large stroke up to 400µm and a stiffness of 0.1N/µm. The quality factor is reduced near 20 via an elastomer part (see Fig. 1). The chosen configuration is similar to a proof mass device with an additive mass of 250 grams placed at the top of the actuator. The volume is $50*32*22mm^3$. Firstly, this mass magnifies the displacement of the actuator (and the electrical input) with less input energy and secondly, it places the resonant frequency of the actuator in the range of frequency where the vibration energy available in the environment is important [4]. The choice of the APA400M-MD is pointed by the fact that the level of vibration is near 20µm in the 100Hz's bandwidth and so, with the amplification due to the quality factor, its stroke reaches the maximal deflection.

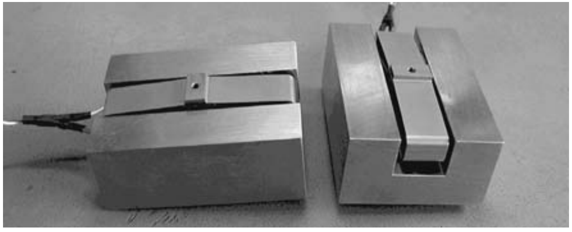


Fig. 1: *Electromechanical device built around APA400M-MD*

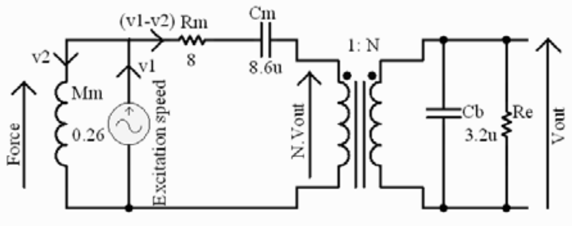


Fig. 2: *electromechanical model*

The model is based on electromechanical analogy (see Fig. 2). This analogy with the electrical behaviour can be used to represent the chosen proof mass configuration with a excitation in speed at the base of the actuator. The intrinsic parameters are measured in a blocked - free configuration at low level.

Theory of energy reclamation

A vibrating piezoelectric device differs from an electrical power source. The complex source impedance (function of the intrinsic parameters of the actuator and the frequency) is not really null and the maximum power that we can transfer to the load is function of its value (see Fig. 3).

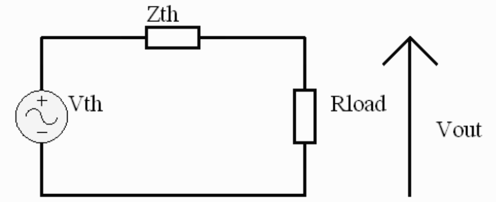


Fig. 3: *Thévenin equivalent model*

From Fig. 2, we can give the Thévenin voltage and impedance:

$$V_{th} = \frac{F}{N} \cdot \frac{Z_e}{(\frac{1}{C_m \omega} + R_m) + Z_e} \tag{1}$$

$$Z_{th} = \frac{Z_m \times Z_e}{Z_m + Z_e} \tag{2}$$

From Fig. 2, we can extract the formulas to obtain the complex mechanical impedance Z_m and the complex electrical impedance of the actuator Z_e :

$$Z_e = \frac{R_e}{1 + j\omega R_e C_b} \tag{3}$$

$$Z_m = \frac{1}{N^2}\left(j\omega M_m + \frac{1}{j\omega C_m} + R_m \right) \tag{4}$$

Where R_e represents the dielectric loss in the ceramic, C_b, the blocked capacitance, M_m, the modal mass, C_m, the modal elasticity and R_m, the mechanical loss.

The maximum average power transfer is realised when the load is equal to the complex impedance of the actuator, $|Z_{load}| = |Z_{th}|$ (see Fig. 3).

With a forced sine vibration at the resonant frequency of the electromechanical device injected at its base, we define the efficiency of the system as the electrical harvesting power compared to the mechanical power injected at the base of the APA400M-MD.

$$\langle P_{mechanic} \rangle = F_{rms} \times v_{2,rms} \times \cos\varphi \tag{6}$$

$$\langle P_{electric} \rangle = V_{out,rms} \times I_{th,rms} \times \cos\theta \tag{7}$$

$$\eta = \frac{\langle P_{electric} \rangle}{\langle P_{mechanic} \rangle} \tag{8}$$

A vibrating piezoelectric generates an AC voltage while the standard electrical components require DC voltages. From this remark, the first stage directly connected to the output of the piezoelectric device is an AC-DC conversion constituted of a bridge rectifier (see Fig. 4).

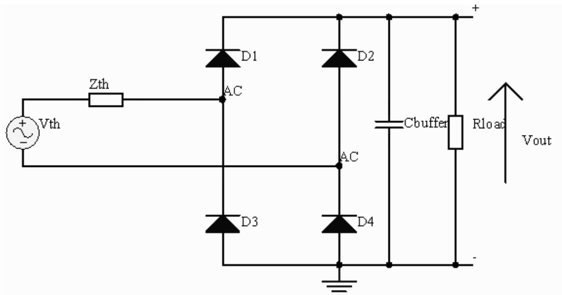


Fig. 4: *AC-DC stage connected to APA400M-MD*

This stage transforms the AC to DC voltage from the piezoelectric actuator but without optimisation of the power flow in the load.

A step-down converter synthesises this active impedance able to adapt the load to the electromechanical impedance.

Several topologies exist on the market and to illustrate this paper, we choose a Flyback converter working in Discontinuous mode (DCM). The figure 5 shows the held topology.

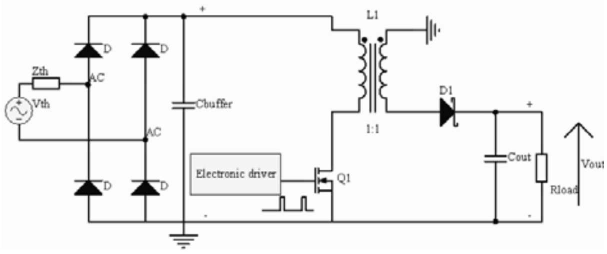


Fig. 5: Schematic of the AC-DC & DC-DC converter used to adapt the piezoelectric impedance

Mainly, the circuit consists of a switching element Q1 with its associated electronics, coupled with a transformer with a 1:1 ratio T1 and a diode D1.

A detailed analysis of the behaviour of the Flyback converter operating in DCM mode is given in [5] and the principal results are the possibility to adjust the input impedance with the duty cycle.

$$\frac{V_{out}}{V_{in}} = DT\sqrt{\frac{R_{out}}{2F_{switching}\times L1}} \qquad (9)$$

$$R_{in} = \frac{2\times F_{switch}\times L_1}{DT^2} \qquad (10)$$

During the switching period, the MOSFET is closed during the interval $\Delta t \cdot T_{swicthing}$ and the rectifier voltage energises the inductor and drives a current through the inductor. During the interval $(1-\Delta t)\cdot T_{swicthing}$, the MOSFET device is turned off and the diode D1 turns on. The energy is transferred to the output with a decrease of the inductor current. The choice of F_{switch} is realised keeping in mind a low power consumption of the electronics devices (i.e. low switching frequency). A custom transformer is designed to minimise the loss inside and the switching frequency is adapted to the maximum power flow.

Experimental set-up

An experimental set-up (see Fig. 6) was designed and implemented. The excitation was generated by an other piezoelectric device (APA120ML) able to generate enough force and stroke to maximise the stroke of the APA400M-MD at its resonant frequency (near 110Hz). The output voltage generated by the APA400M-MD was measured via the AC-DC rectifier or the impedance adaptation. Accelerometer sensors measured in real time the amplitude of the reaction mass and the injection speed to give the mechanical power.

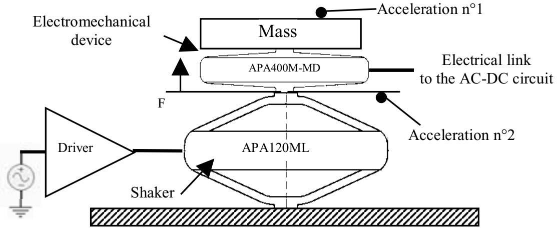


Fig. 6: Synoptic of the experimentation

Results and discussions

The first curves (Fig. 8) shows the unloaded DC output voltage at the output of the bridge rectifier at 20µm vibration.

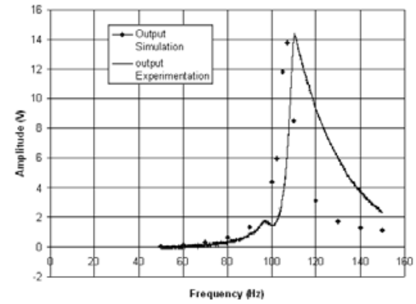


Fig. 7: DC Output voltage comparison between experiments and simulation - Unloaded.

The experiments are very similar to the simulation with a small drift on the resonant frequency.

To conclude these first experimental steps, we trace the efficiency and the output power at different excitation level of the electromechanical device coupled with the AC-DC circuit (see Fig. 8 & 9).

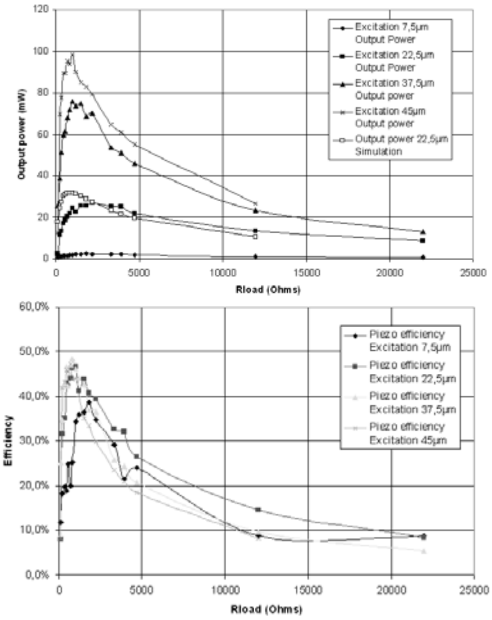


Fig. 8 & 9: Output power & efficiency of the APA400M-MD (Measurement & simulation)

The efficiency is function of the excitation level. For a stroke under 200µm, the efficiency is not optimum. At high level (upper 200µm), the efficiency reaches up to 48%. With these values and with only 200mW of mechanical power, it's possible to obtain up to 95mW (with up to 600µm on the APA400M-MD) at the output of the rectifier bridge (the limit is the stroke of the APA400M-MD).

The optimum power flow is obtain with a optimum load near 2kΩ. This value is used for the next tests to validate the impedance adaptation. The switching frequency of the Flyback converter is placed at 12kHz and the transformer is composed of two wiring inductors of 5mH. The chosen diodes are schottky diodes to reduce the direct voltage. The duty cycle is placed near 20% to synthetise an optimum load around 2kΩ.

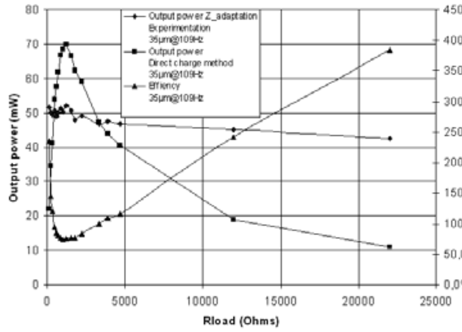


Fig. 10: *Output power & efficiency of the APA400M-MD with Flyback circuit & comparison with direct charge method*

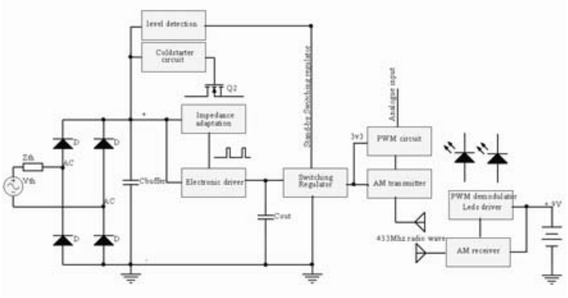
Compared to the direct charge method, under and above the optimum load, the benefit of the circuit is up to 400%. Of course, at the optimum, the loss in the DC-DC converter breaks this benefit and the efficiency is near 75% at this level.

Demonstrator with a possible application

Based on the previous results, a self powered demonstrator was designed and implemented. This demonstrator shown the possibility to realise a wireless and self-powered sensor able to be placed on any structure where enough vibration energy is available to transmit a data towards a receiver to read, store the values.

Of course, the self-powered system included all the discussed electrical functions but it added a cold starter to charge in direct charge mode the buffer capacitor and provide enough electrical energy to start the other functions, a switching regulator, the electronics functions to transform any analogue voltage in digital signals based on a PWM 433Mhz AM transmitter to send up to 50m the signal.

The receiver included a 433Mhz AM receiver, a PWM demodulator and a 20 leds driver to realise a bargraph able to give the value of the analogue signal send via the self-powered transmission. (see Fig 11 & 12).



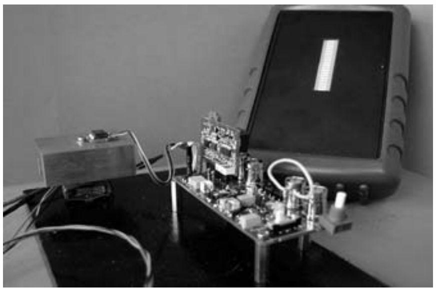


Fig. 11 & 12: *Synoptic of the demonstrator*

Summary and conclusion

This paper discussed an energy harvesting system based on an electromechanical device mounted in proof mass configuration able to produce electrical power from vibration injected to its base. The efficiency of the device with an AC-DC converter reached up to 48% with only 45µm vibration. This results shown the possibility with a high efficiency to obtain large electrical output power. Coupled to a step-down converter, the electrical circuit is able to optimise the power flow in a load and the harvested power was able to supply a AM transmitter and realised a wireless and self powered sensor.

Acknowledgements

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