ABSTRACT

Aerospace structural maintenance (fuselage, wings) is a major component of operational costs which requires aircraft to be grounded and some of its parts to be dismantled in order to proceed to inspection. In order to allow in situ monitoring, Structural Health Monitoring (SHM) has been proposed where sensors and actuators are integrated on the structure. To avoid extensive wiring of the nodes, wireless sensors and actuators are attractive but should be self powered to fully benefit from them. One idea is to convert the mechanical energy (vibrations) available all over an aircraft into electricity using piezoelectric materials. This work investigates the potential of strain-based energy harvesters (as opposed to inertial harvesters) to supply wireless nodes on typical aircraft structures. A simple model is used to describe typical dynamic behavior of aircraft components: a beam representing the whole wing subjected to atmospheric effects and a plate representing a fuselage panel. Various configurations of piezoelectric materials are tested such as bulk PZT, PZT fiber composite and Polyvinylidene Fluoride (PVDF) in order to evaluate the influence of their characteristics (size, polarization, electrodes’ shape, capacitance…) on the harvested power. The results show that for a typical excitation of the beam (10 Hz and 56 µdef), the energy produced is up to 100 mJ with bulk PZT. From the literature, this appears sufficient for measurements (10 nJ) or RF transmission (25 µJ) but not for both at the same time depending on the kind of piezoelectric material. Therefore, strain-based energy harvester could be used for supplying wireless sensor nodes but they would not allow real time measurement. However this approach is a simple and convenient way to scavenge energy compared to other kinds of harvesters (inertial, solar…) since it amounts to bonding a piezoelectric material on a flexible surface.

Keywords: Power harvesting, energy harvesting, piezoelectric, piezoelectric fiber composite, vibration energy, structural health monitoring.
INTRODUCTION

In applications such as Structural Health Monitoring (SHM) of aerospace structures, sensors and actuators are required to be installed permanently and transmit monitoring signals to a base. In order to reduce the footprint of the wiring required for powering these units, power harvesting from ambient vibration sources has been proposed. Power can be harvested either from tonal sources arising from natural modes of vibrations of wings for example, or broadband turbulent boundary layer or jet noise.

Piezoelectric harvesting devices have been proposed for energy harvesting from ambient vibration sources [1]. Two approaches can be identified for mechanical energy harvesting: i) resonant devices where a mass-spring-damper system formed of a piezoelectric material is excited by vibrations of the supporting structure and ii) non-resonant approaches where the strain of the structure is directly transferred to the piezoelectric material.

Bulk or monolithic piezoceramics (PZT) have been used mostly for energy harvesting and, while they offer a large sensitivity to strain, they suffer from brittleness [2]. Polyvinylidene fluoride (PVDF) piezoelectric films offer an interesting alternative to PZT, with increased material flexibility. A number of electrode patterns have been proposed for PVDF, including inter-digital transducers [3]. However, PVDF suffer from low sensitivity and connection problems. Active Fiber Composites (AFC) [4], and then Macro Fiber composites (MFC) [5], also called Piezoelectric Fiber Composites (PFC), have been more recently developed to offer directional sensing and actuation with electrode connection through screen-printing tools. Greater sensitivity is naturally obtained along the axis of the piezoelectric fibers used in the fabrication of the transducer which are embedded in an epoxy matrix and sandwiched between two sets of inter-digital electrodes (IDT). PFC have been compared with bulk PZTs and Quick Pack actuators for charging a battery and for a given polarization direction [6-7].

It is the purpose of this paper to present a thorough comparison of energy harvesting for different piezoelectric harvesting devices and two polarization directions (when applicable), and evaluate the performance for representative aircraft structural loads.

ENERGY HARVESTING

A number of electrical circuits have been proposed for harvesting power form a piezoelectric device [8]. Two configurations are presented in the following for dissipation of power in a resistive load and for storage of energy in a capacitor. Although more advanced circuits could have been used, these simple circuits were chosen for comparison purposes between the piezoelectric harvesting devices. It is therefore expected that better performance could be achieved with advanced circuits.

Dissipation in a resistive charge: Figure 1a) presents the circuit which was used to study the effect of the resistive load $R_L$ on the power dissipated and to determine an optimal resistive charge.
As the resistive load has an impedance much higher than the measurement device (oscilloscope), a small measurement resistor $R_i$ (typically 1 kΩ or 10 kΩ) is used to obtain the current $I$ in the circuit. Then, by measuring the voltage $U_i$, current and power in the circuit can be found. For the case of optimal voltage and power, where the maximum power is dissipated, the following can be written:

$$I_{\text{opt}} = \frac{U_i}{R_i}$$  \hspace{1cm} (1)

$$U_{\text{Lopt}} = (R_i + R_{\text{Lopt}}) I_{\text{opt}}$$  \hspace{1cm} (2)

$$\langle P_{\text{opt}} \rangle = \frac{U_{\text{Lopt}}^2}{R_i + R_{\text{Lopt}}} = (R_i + R_{\text{Lopt}}) I_{\text{opt}}^2$$  \hspace{1cm} (3)

**Storage in a capacitor**: The circuit presented in Figure 1b) is used to charge a capacitor $C_L$ of 93.4 µF, simulating the charging of a battery for real applications. A switch is used in the circuit to allow the capacitor to discharge when connected to a load (not shown in the figure).

**Piezoelectric harvesting devices**

A number of piezoelectric harvesting devices have been compared within this work, with different polarization directions, piezoelectric coupling coefficients and type. Table I summarizes the properties of the devices used.

**Table I: Properties of the piezoelectric harvesting devices used in the study.**

<table>
<thead>
<tr>
<th>Capacitance, nF</th>
<th>Polarization</th>
<th>Size of the active in mm (Mass in g)</th>
<th>Piezoelectric coefficient $d_{33}$, pC/N</th>
<th>Type</th>
<th>Manufacturer</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM - P1 - 0.66 nF</td>
<td>0.66</td>
<td>[3-3] 14<em>28</em>0.18 (0.785)</td>
<td>400</td>
<td>Composite</td>
<td>Smart Material Corp.</td>
</tr>
<tr>
<td>SM - P1 - 1.13 nF</td>
<td>1.13</td>
<td>[3-3] 14<em>28</em>0.18 (0.785)</td>
<td>400</td>
<td>Composite</td>
<td>Smart Material Corp.</td>
</tr>
<tr>
<td>SM - P2 -</td>
<td>23.2</td>
<td>[3-1] 13<em>28</em>0.18 (0.683)</td>
<td>-170</td>
<td>Composite</td>
<td>Smart Material Corp.</td>
</tr>
<tr>
<td>ERF</td>
<td>1.53</td>
<td>[3-3] 20.5<em>41</em>0.25 (2.207)</td>
<td>280</td>
<td>Composite</td>
<td>ERF Produktion Würzburg GmbH</td>
</tr>
<tr>
<td>BM 500</td>
<td>15.29</td>
<td>[3-1] 25.4<em>50.8</em>1 (10.519)</td>
<td>-175</td>
<td>Bulk</td>
<td>Sensor Technology Ltd.</td>
</tr>
<tr>
<td>PVDF (Polyvinylidene fluoride)</td>
<td>1.36</td>
<td>[3-1] 50.8<em>50</em>0.11 (0.508)</td>
<td>-23</td>
<td>Polymer</td>
<td>Measurement Specialties</td>
</tr>
</tbody>
</table>
In order to validate the experimental performance of the piezoelectric harvesting devices in power harvesting with respect to both strain and frequency, a few indications are given. For a piezoelectric, the electrical charges \( Q \) generated are proportional to the strain experienced by the device. The optimal current \( I_{opt} \) is the time derivative of the charges and thus, as the frequency of the measured signal increases, this current will increase proportionally. Therefore, the optimal current is proportional to both the strain and the frequency. On the other hand, maximum power will be harvested for a load with impedance equal to the magnitude of the impedance of the piezoelectric device. Since the piezoelectric device behaves essentially as a capacitor its impedance is inversely proportional to the frequency. Therefore, the optimal resistor \( R_{opt} \) will also be inversely proportional to frequency. Following these observations, the global behaviour for optimal power harvested can be written as:

\[
\begin{align*}
R_{opt} & \propto \frac{1}{\text{frequency}} \\
I_{opt} & \propto \text{strain} \times \text{frequency}
\end{align*}
\]

which leads to the optimal power:

\[
\langle P_{opt} \rangle \propto \text{frequency} \times \text{strain}^2
\]

Using constitutive relations of piezoelectricity and assuming that a piezoelectric material can be described as a plane capacitor, the optimal power becomes:

\[
U_{opt} \propto \frac{d_{3x} \cdot S_s \cdot t}{K_T}
\]

\[
\langle P_{opt} \rangle \propto \frac{C \cdot t^2}{K_T^2} \cdot d_{3x}^2 \cdot S_s^2 \cdot \text{f}
\]

where \( t, S, K_T \) are the inter-electrodes space, strain, and dielectric constant, respectively.

**EXPERIMENTAL SETUP**

Non-homogeneous flow encountered by an aircraft will translate into various types of excitation on the structure. Among these excitations, one very energetic one will be in the form of flexural vibration of the wings. It was chosen in this work to simulate such an excitation by using a simple clamped beam with representative strain (56 \( \mu \text{def} \)) and frequency (10 Hz) [9-10].

Figure 2a) presents the beam used while Figure 2b) presents one the piezoelectric harvesting devices used. A number of identical beams with dimensions 542 mm x 50.8 mm x 6.35 mm were used and excited at the free end with a shaker capable of generating large displacement at low frequency. The piezoelectric harvesting devices were bonded close to
the clamped end, where maximum strain levels are obtained for such a configuration, and maximum harvested power will be obtained.

![Fig. 2: a) Clamped beam and b) piezoelectric fiber composite SM P1 – 1.13 nF.](image)

The shaker excites the beam at a given frequency and with a given displacement. The shaker is driven by a frequency generator and connected to the beam through a stinger. In order to compare all piezoelectric harvesting devices under similar conditions, excitation levels are adjusted such that the same strain is measured by the devices. The strain is simulated through analytical calculation from the displacement obtained from time integration of either acceleration or velocity measured at the excitation point using flexural beam theory under clamped-free conditions. The acceleration is measured with an accelerometer bonded at the excitation point while the velocity is measured using a laser vibrometer at the same point. This approach allows each piezoelectric device to experience the same strain level.

**RESULTS**

The experimental results are presented for the piezoelectric harvesting devices listed in Table I. Results are presented for both power dissipation in a resistive load and storage of energy in a capacitor.

**Dissipation in a resistive load**

Figure 3 shows the dissipated power as a function of the resistive load $R_L$ for the operating point \{10 Hz; 56 $\mu$def\}. The first observation is that the similar behaviour is obtained for different piezoelectric harvesting devices, where a clear maximum can be localized, corresponding to the optimal resistive load $R_{\text{Lopt}}$. As already mentioned, this maximum dissipated power is obtained when the magnitude of the impedance of the load, $R_{\text{Lopt}}$, is equal to the magnitude of the impedance of the piezoelectric harvesting device, $|Z_p|$. Figure 3 also shows that the optimal resistive load $R_{\text{Lopt}}$ varies for different piezoelectric harvesting devices.
Fig. 3: Dissipated power for the operating point \{10 \text{ Hz}; 56 \, \mu \text{def}\} for a) \{3-3\} polarized piezoelectric harvesting devices and b) \{3-1\} polarized piezoelectric harvesting devices.

First observations show that two groups can be distinguished: i) piezoelectric harvesting devices polarized in \{3-3\} (Figure 3a) and ii) piezoelectric polarized in \{3-1\} (Figure 3b). In fact, a factor over 10 has been obtained for the optimal resistive loads $R_{L_{opt}}$ between both groups. This observation can be explained by the different capacitance associated with both groups, as shown in Table II.

As shown in Figure 4 for the bulk piezoelectric (BM 500), the optimal resistive load also depends on the excitation frequency. The level of excitation itself has no impact on the value of the optimal resistive load but will obviously affect the level of dissipated power, as discussed next.

Figure 5 shows the dissipated power density (per unit volume) as a function of both the strain level (Figure 5a) and the frequency (Figure 5b). The maximum level for dissipated power (650 $\mu$W/cm$^3$) is achieved for an excitation at 18 Hz and a strain level of 56 $\mu$def for the piezoelectric device SM P1 – 1.13 nF.
Figure 5 also compares the various piezoelectric harvesting devices for the same excitation. Again, two groups are distinguished: i) piezoelectric harvesting devices polarized in {3-3} and ii) piezoelectric harvesting devices polarized in {3-1}.

Among those polarized in {3-3}, the SM P1 – 1.13 nF – provides more power than the SM P1 – 0.66 nF – and the ERF. This illustrates the fact that for similar piezoelectric coefficients (SM P1 0.66 and 1.13 nF), the power obtained is greater for a higher capacitance. In fact, for an increase of 71 % (|0.66 - 1.13| / 0.66) in the capacitance, the mean power dissipated increases by 28 % (|265.31 - 339.99| / 265.31). However, the performances of the piezoelectric device SM P1 – 0.66 nF – are better than those of the ERF (1.52 nF) even if the capacitance of the latter is higher by 132 %. It therefore appears that the piezoelectric coupling coefficient has a greater effect on the dissipated power than the capacitance of the piezoelectric material polarized in {3-3}.

As for the devices polarized in {3-1}, the SM P2 provides the most dissipated power, in front of the BM 500. Their piezoelectric coupling coefficient is similar but their capacitance is different. The capacitance is higher for the SM P2 (23.2 nF) than for the BM 500 (15.29 nF). This also confirms that higher dissipated power is obtained with higher capacitance values.

Finally, the two groups of polarization can be compared. It appears that the SM P1 – 1.13 nF – provides the highest power dissipated power, in front of the SM P2 and the SM P1 – 0.66 nF -. The selected PFCs produce the most power among the piezoelectric harvesting devices tested. On the other hand, the ERF provides the least dissipated power. One explanation for this would be the quality of fabrication which seems to be beyond the quality of fabrication of other PFCs: fibers are not properly aligned and do not have the same length. Another explanation is that the fibers for ERF are circular instead of rectangular, which impairs the contact between the electrodes and the piezoelectric material itself. It should however be mentioned that the PFCs from ERF are not to be used in small patches like the ones used in this paper but rather be integrated into larger structures (such as wings or fuselage) for excitation and measurement.
Table II presents the estimated power density calculated using Eq. (7) for the same operating point \{10 Hz; 56 \text{ \mu def} \}. The observations made earlier correlate well with the predictions in Table II. The SM P1 – 1.13 nF – has the highest power density while the ERF is the lowest one. The other three piezoelectric harvesting devices have similar power density.

### Table II: Predicted power density at \{10 Hz; 56 \text{ \mu def} \}.

<table>
<thead>
<tr>
<th>Relative permittivity</th>
<th>Piezoelectric coefficient ( d_{33} ), pC/N</th>
<th>Capacitance, nF</th>
<th>Inter-digital spacing, mm</th>
<th>Volume, mm(^3)</th>
<th>( C \cdot \frac{V}{K} \cdot \frac{d_{33}}{cm^3} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM - P1 - 0.66 nF</td>
<td>1850</td>
<td>400</td>
<td>0.66</td>
<td>0.5</td>
<td>70.56</td>
</tr>
<tr>
<td>SM - P1 - 1.13 nF</td>
<td>1850</td>
<td>400</td>
<td>1.13</td>
<td>0.5</td>
<td>70.56</td>
</tr>
<tr>
<td>SM - P2</td>
<td>1850</td>
<td>-170</td>
<td>23.2</td>
<td>0.18</td>
<td>65.52</td>
</tr>
<tr>
<td>ERF</td>
<td>1850</td>
<td>280</td>
<td>1.53</td>
<td>0.5</td>
<td>210.21</td>
</tr>
<tr>
<td>BM 500</td>
<td>1750</td>
<td>-175</td>
<td>15.29</td>
<td>1</td>
<td>1290.32</td>
</tr>
</tbody>
</table>

**Storage in a capacitor**

In this part of the work, the resistive load is replaced by a capacitor to investigate the performance of the piezoelectric harvesting devices in an energy storage configuration, using the electrical circuit presented in Figure 1b). The capacitor used in the following was chosen to have the value 93.4 \text{ \mu F}, for comparison purposes between the piezoelectric harvesting devices. In a practical application, the capacitor would be used to store energy that would later be used to power a sensor or an actuator for structural health monitoring.

In the following, the time required to charge the capacitor is presented together with the power transferred by the piezoelectric harvesting device to the capacitor and the energy stored in the capacitor.

![Fig. 6: Charging of the capacitor (93.4 \text{ \mu F}).](image)

The charging time of the capacitor is first presented in Figure 6. It appears that the charging time varies significantly with the type of polarization. Piezoelectric harvesting devices polarized in \{3-1\} (SM P2 and BM 500) charge much faster than the piezoelectric harvesting devices polarized in \{3-3\}. This is explained by the fact that the current generated by the devices polarized in \{3-1\} is much larger than the current generated by those polarized in \{3-3\}. This means that for a given time period, more electrical charges are collected at the
electrodes. Nevertheless, once normalized by the volume of the piezoelectric material, the final voltage reached by the piezoelectric harvesting devices polarized in \{3-3\} is much higher. This was expected since the final voltage is proportional to the piezoelectric coupling coefficients \(d_{3x}\) and the piezoelectric harvesting devices polarized in \{3-1\} have larger coefficients.

Figure 7 presents the energy density. Higher final voltage is associated to higher energy density \(E_v\) for piezoelectric harvesting devices polarized in \{3-3\}:

\[
E_v = \frac{1}{2} \cdot C_{st} \cdot U^2
\]  

\(\text{Fig. 7: Stored energy in the capacitor.}\)  
\(\text{Fig. 8: Power at 95\% of max. voltage.}\)

However, when plotting the power transmitted by the piezoelectric harvesting device at 95\% of the maximum voltage (Figure 8), the piezoelectric harvesting devices tend to behave in a more similar manner. This is due to the faster charging of the piezoelectric harvesting devices polarized in \{3-1\}. Thus, although the quantity of energy is smaller for this latter case, the power transmitted is nearly equivalent due to shorter charging time.

CONCLUSIONS

This paper presented an experimental comparison of different piezoelectric energy harvesting devices for application in structural health monitoring. An experimental setup was proposed to reproduce simple vibration behaviour of an aircraft wing with respect to frequency and strain level.

Two distinct groups of piezoelectric harvesting devices were investigated: i) piezoelectric harvesting devices polarized in \{3-3\} and ii) piezoelectric harvesting devices polarized in \{3-1\}. Two configurations were tested: i) power dissipation in a resistive load and ii) energy storage in a capacitance.

It was noted that the optimal voltage is linearly dependent on the strain, but independent of the frequency. The optimal current was shown to be linearly dependent on both the frequency and the strain level. The power dissipated in a resistive load was shown to be linearly dependent on the frequency but quadratically related to the strain level. As for the
piezoelectric material itself, the dissipated power is a linear function of the capacitance and inversely proportional to the relative permittivity. This dissipated power is also a quadratic function of the inter-digital spacing and the piezoelectric coupling coefficient.

Literature indicates that power density in the order of 100 μW/cm³ is satisfying for many applications, including structural health monitoring. The results presented in this work are in accordance with this. To increase the harvested energy, larger devices will be required.

Future work will investigate the use of more advanced harvesting circuits and integration with a structural health monitoring device capable of generating waves into the structure and measuring its response.

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