Assessment of the Potential for Micro Energy Harvesting in a Fixed-Wing MAV Configuration

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The design process of a structure-embedded cantilevered harvester has been carried out to assess the power that can be harvested to extend the endurance of fixed-wing MAVs. The study has been carried out using a code based on an electro-mechanical model coupling the mechanics equations and piezoelectric effect. The harvester is a bi-morph symmetrical beam including two piezoelectric layers and a central structural layer. A mass is added at the tip to increase the potential under a base excitation at the root of the beam. A detailed analysis of the excitations and frequencies over a MAV shaped model from previous studies was performed to size the harvester at its optimal proportions. The results show the primary target set for the harvester cannot be achieved in fixed-wing MAVs with the present technology because of the low power outputs and the loss of flight time due to the mass addition. The evaluation of a possible multifunctional use of the harvester show that even though the endurance cannot be increased, extra electronics could be added to improve the features of an aerial vehicle powered by piezoelectric harvesters.

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A$</td>
<td>area</td>
<td>$[\text{mm}^2]$</td>
</tr>
<tr>
<td>$a_{\text{base}}$</td>
<td>base acceleration</td>
<td>$[\text{m/s}^2]$</td>
</tr>
<tr>
<td>$B_f$</td>
<td>scalar modal forcing coefficient.</td>
<td>$[\text{kg}]$</td>
</tr>
<tr>
<td>$C$</td>
<td>damping coefficient</td>
<td>$[\text{N-s/m}]$</td>
</tr>
<tr>
<td>$C_L$</td>
<td>lift coefficient</td>
<td>-</td>
</tr>
<tr>
<td>$C_D$</td>
<td>drag coefficient</td>
<td>-</td>
</tr>
<tr>
<td>$C_p$</td>
<td>capacitive coefficient</td>
<td>$[\text{F}]$</td>
</tr>
<tr>
<td>$D$</td>
<td>electric displacement</td>
<td>$[\text{C/m}^2]$</td>
</tr>
<tr>
<td>$d$</td>
<td>piezoelectric constant</td>
<td>$[\text{m/V}]$</td>
</tr>
<tr>
<td>$E$</td>
<td>electric field</td>
<td>$[\text{V/m}]$</td>
</tr>
<tr>
<td>$E_B$</td>
<td>energy provided by batteries</td>
<td>$[\text{J/kg}]$</td>
</tr>
<tr>
<td>$f$</td>
<td>frequency</td>
<td>$[\text{Hz}]$</td>
</tr>
<tr>
<td>$K$</td>
<td>stiffness of the structure</td>
<td>$[\text{N/m}]$</td>
</tr>
<tr>
<td>$k_{ij}$</td>
<td>electromechanical coupling</td>
<td>-</td>
</tr>
<tr>
<td>$L$</td>
<td>length / lift</td>
<td>$[\text{mm}]/[\text{N}]$</td>
</tr>
<tr>
<td>$M$</td>
<td>mass of structure</td>
<td>$[\text{kg}]$</td>
</tr>
<tr>
<td>$m$</td>
<td>mass per length</td>
<td>$[\text{kg/m}]$</td>
</tr>
<tr>
<td>$m_x$</td>
<td>ass relative to length $x$</td>
<td>$[\text{kg}]$</td>
</tr>
<tr>
<td>$P$</td>
<td>poling direction</td>
<td>$[\text{C/m}^2]$</td>
</tr>
<tr>
<td>$P_{\text{out}}$</td>
<td>electrical power generated</td>
<td>$[\mu\text{W}]$</td>
</tr>
</tbody>
</table>

The specific power density $P_{\text{dens}}$, resistance $R$, generic coordinate $r$, strain vector / wet surface $S$, stress vector $T$, thickness $t$, volume $V$, voltage generated or extracted $V_{\text{out}}$, modal analysis constant $\lambda_{\text{m}}$, coupling coefficient matrix $\Theta$, mechanical damping ratio $\xi$, propulsion efficiency $\eta_p$, efficiency of the batteries $\eta_b$.

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1 A similar version of this paper, made in co-authorship with Prof. J.M.M. Sousa, has been accepted for oral presentation in the AIAA SciTech Forum to be held on 5-9 January 2015 in Kissimmee, Florida, United States of America.
I. Introduction

UAVs are certainly a kind of air vehicle that has captured the attention of a significant amount of researchers and manufacturers in Aeronautics. The reason of its success is the capability of these vehicles to gather data, provide surveillance and explore in hostile, unknown or unreachable terrains. That combined with their relatively low manufacturing cost has encouraged the creation of UAV programs worldwide. However a new class of UAV has more recently emerged, which is characterized by an order of magnitude smaller in length and two orders of magnitude lighter in weight. This new class is called the micro aerial vehicle (MAV). These vehicles have been defined to have length dimensions no larger than 15 cm with a gross take-off weight of approximately 200g or less.

As a new class of aerial vehicle, these systems face many unique challenges that make their design and development difficult, such as the aerodynamic behavior of the lifting surfaces at a low Reynolds flow. This condition produces complex phenomena difficult to describe with analytic methods. Improving the endurance is another major issue concerning the MAV design due to the necessity of improving their performance for longer missions without penalizing on the dimension requirements.

Specifically focusing on the endurance, ongoing projects are trying to build MAVs capable to flight for more than an hour, which is more than twice the endurance of the current designs performance. Endurance of a vehicle is inversely proportional to the power required to maintain steady state level flight which implies the necessity to minimize the power required to increase the endurance. Compared to full-scaled aircrafts, MAVs use a higher percentage of propulsion mass. This fact leads to about the consideration of using power sources able to provide higher energy density \( \frac{\text{Energy}}{\text{prop.mass fract}} \) or, even better, a double function: a structure able to provide power as well. Micro-engines are being studied to provide quick recharging on electronic devices but applications to the propulsion of aerial vehicles are also being carried out. Harvesters are, however, the most common approach on improving MAVs flight time highlighting solar cells as the principal solution. This is the reason why the study of piezoelectricity focused on aeronautical applications is still a challenge to be accomplished. Hence the aim of this work is to clarify whether it is plausible or not to achieve enough power for propulsion applications in MAVs using the aforementioned solution.

II. Requirements of the problem

The design of piezoelectric harvesters is subjected to several restrictions because these depend on external factors to gather the energy. Therefore it is mandatory to find which are those restrictions and select standard data so that the tests of the piezoelectric harvester may be consistent with the environment where the harvester is operated.

The first requirements arise from installing the harvester inside the vehicle. Then, basic parameters are needed to define the flight conditions and standard dimensions of the vehicle. From the data obtained in [1], a theoretical model of a fixed-wing MAV was made. Table 1 shows the parameters of the model and upper/lower boundaries in case some adjustments are needed.
Another basic requirement is to provide the maximum power allowed. This means selecting a material with a high piezoelectric coefficient $d_{ij}$. This parameter relates the applied strain over the material with the provided voltage. Lead Zirconate Titanate (PZT) based devices are the best option to obtain positive results in terms of power output. Furthermore, its capability to be doped enhance the performance and offer a large range of applications. A part from the material, the mode how the harvester is designed also affects the power provided. The mode is the configuration relating the orientation of piezoelectric dipoles (electric field) with the direction of the strain applied. Two basic modes are distinguished:

- mode {3-1}: The electric field and strain vectors are perpendicular
- mode {3-3}: The electric field and strain vectors are parallel

In general terms, mode {3-3} is related with a higher piezoelectric coefficient, usually around $d_{33} \sim 2.4$ times higher than the {3-1} mode. But the layouts of harvesters based in this mode introduce some difficulties, ending up with worst performance than the alternative mode. In order to force the strain vector to be parallel with the electric field, the piezoelectric electrodes must be interdigitated in the same plane, as shown in Figure 1.

The non-straight electric field vector is the reason why the overall efficiency of the harvester is worst even though the piezoelectric coefficient may be larger. On the other hand, the {3-1} mode is simply implemented via a three-layered harvester containing two piezoelectric plates acting as electrodes and a structural layer keeping away both electrodes, as shown in Figure 2.
In addition, mode {3-1} has been considered for the tests and simulations performed in the present study due to the fact that the negative effect of the mode {3-3} is only detected when carrying out experimental tests. The reason is that modeling equations assume the region of the piezoelectric element under the electrode is electrically inactive (see Figure 3), whereas the section between the electrodes utilizes the full $d_{33}$ effect; hence the non-straight electric field vector is voided.

Figure 3 {3-3} mode layout assuming simplifications

III. Endurance Modeling

Improving the endurance is the primary goal of installing piezoelectric harvesters. Thus, there has to be a criterion to evaluate how adding new components to the vehicle affects its maximum flight time. In fact known expressions to estimate the endurance of an aircraft can also be applied to this case namely the Breguet equation. The method used in this work is based in (Anton, S. R)\(^2\) [2][3] works and relates with the basis of the already mentioned Breguet equation. The following expression is valid for electric powered aircraft in a steady level flight:

$$t_E = \frac{E_B \eta_B}{\frac{3}{2} W_T - P_{\text{harv}} \left( \frac{\rho_0 SC_I^3}{2C_D^2} \right) \frac{1}{2} \eta_P}$$

When applying Eq. (1), it is useful to compare the results of the endurance of an MAV with the ones obtained in the same vehicle without any kind of harvesters. To do so, the endurance may be expressed as an increment value that can also be normalized with the resulting value from a non-harvesting MAV.

A linear series Taylor expansion of $t_E$ about the point $P_{\text{harv}} = 0$ can be used to formulate the normalized change in flight endurance, as follows:

$$\frac{\Delta t_E}{t_E} \approx \frac{\Delta m_B}{m_B} = \frac{3}{2} \frac{\Delta m_B + \Delta m_{ST} + \Delta m_{\text{harv}}}{m_T} + \frac{p_{\text{harv}} \Delta m_{\text{harv}}}{p_{\text{ave}} m_B}$$

The simple aerodynamic model used in the derivation naturally adds several assumptions about the flight of the aircraft and the ambient operating conditions, namely imposing constant conditions. The formulation, however, can be used to provide the effects of adding energy harvesting systems to electric powered UAVs and MAVs.

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\(^2\) The original development of the theory has been presented by Thomas et al [6] and cited by Anton [2].
IV. Electro-Mechanical Coupled Equations

The simulations of piezoelectric materials have to be studied with a coupled model from mechanics and piezoelectric equations. The model used in the project is based in the energy method approach proposed by duToit [4]. Both the constitutive equations of piezoelectricity and the equations describing the dynamics of a cantilever beam are presented here, as well as the final coupled equations.

The description of the piezoelectric constitutive equations can be synthesized as follows.

In one hand, the Hooke’s law relates the mechanical stress \( \mathbf{T} \) and strain \( \mathbf{S} \):

\[
S_{ij} = s_{ijkl} T_{kl}
\]

where \( s_{ijkl} \) is the compliance or inverse stiffness.

In the other hand, the expression relating the electric field \( E \) with the electric displacement \( D \) is defined as:

\[
D_i = \varepsilon_{ij} E_j
\]

where \( \varepsilon_{ij} \) is the permittivity.

These two matrix expressions can be combined into coupled equations that adopt the form:

\[
\{S\} = \{s^E\}\{T\} + \{d^E\}\{E\}
\]

\[
\{D\} = [d]\{T\} + [\varepsilon^T]\{E\}
\]

This expression is called the (S-D) form of the coupled equations, being \( S \) and \( D \) the dependent variables. In Eq. \( (5) \)\{d\} and \( \{d^E\} \) represent the matrix of the direct and converse piezoelectric effect, respectively. The superscript \( E \) denotes strain applied at zero or constant electric field and superscript \( T \) denotes zero or constant stress.

The governing equations are the link between the constitutive equations of piezoelectricity and the Euler-Bernoulli beam equation. Deriving the expressions through an energetic approach leads to the equations:

\[
M \ddot{r} + C \dot{r} + K r - \Theta \dot{\nu} = B_f \ddot{\nu}_B
\]

\[
\Theta \dot{r} + C_p v + q = 0
\]

where each term is defined as: Mass \( (M) \), stiffness \( (K) \), coupling \( (\Theta) \) and capacitive \( (C_p) \) matrices. The variable \( \mathbf{r} \) is defined as a normalized displacement and \( \mathbf{v} \) represents voltage. The terms on the right side of the equations are the forcing vector \( B_f \) and the base excitation \( \ddot{\nu}_B \).

At last, the expression of the Euler-Bernoulli beam theory is used to obtain an expression of the modal shape of the beam.

\[
\varphi_{nr} = K \left[ \cosh(\lambda_n x) - \cos(\lambda_n x) + \frac{(\cosh(\lambda_n L) + \cos(\lambda_n L)) \cdot (\sin(\lambda_n x) - \sinh(\lambda_n x))}{\sin(\lambda_n L) - \sinh(\lambda_n L)} \right]
\]
Subsequently, the modal shape is introduced in the governing equations that are solved through Laplace transform leading to the final equations

\[ \left| \frac{r}{B_f w_B} \right| = \left| \frac{1}{K} \frac{\sqrt{1 + (a\Omega)^2}}{\sqrt{[1 - (1 + 2\xi_m a)\Omega]^2 + [(2\xi_m + (1 + \kappa^2)a)\Omega - a\Omega^3]^2}} \right| \]

\[ \left| \frac{v}{B_f w_B} \right| = \left| \frac{1}{|\theta|} \frac{\alpha\kappa^2\Omega}{\sqrt{[1 - (1 + 2\xi_m a)\Omega]^2 + [(2\xi_m + (1 + \kappa^2)a)\Omega - a\Omega^3]^2}} \right| \]

\[ \left| \frac{P_{out}}{B_f w_B} \right| = \left| \frac{\omega_1^2}{K} \frac{\alpha\kappa^2\Omega^2}{[1 - (1 + 2\xi_m a)\Omega]^2 + [(2\xi_m + (1 + \kappa^2)a)\Omega - a\Omega^3]^2} \right| \]

It must be mentioned that the addition of a mass at the tip of the beam does not change the shape of these expressions. Such change would affect the coefficient matrices of the governing equations only.

V. Results

A complete analysis was carried out to study the performance of a cantilevered harvester. This included:

- Base excitation and frequency extractions
- Analysis of the response for different materials
- Simulation of the device in a range of possible shapes.
- Endurance improvement study

For the first part of the study a model performed by Duarte da Cámara [5] was used to extract values of fluctuations on \( C_L \) and \( C_D \) over a wing with sinusoidal leading edge. The parameters defining the wing surface and free-stream conditions are listed in Table 2:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chord (( c ))</td>
<td>0.25</td>
<td>m</td>
</tr>
<tr>
<td>Aspect ratio (( \Delta ))</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>Air speed (( v ))</td>
<td>9.35</td>
<td>m/s</td>
</tr>
<tr>
<td>Air density (( \rho ))</td>
<td>1.22</td>
<td>kg/m³</td>
</tr>
</tbody>
</table>

A 45 seconds simulation with the presented configuration was performed (see Figure 1) thus allowing to establish the base excitation and the target frequency that will be used to perform the simulations of the harvester. The processing of the data provided in Table 1 yielded the range of values at which the harvester simulations are to be carried out:

\[ 0.2 \leq a_{base} \leq 0.77 \text{ [m/s}^2\text{]} \]

\[ 0.8 \leq f \leq 1 \text{ [Hz]} \]
In view of the previous results, it is clear that the material sought needs to respond not only under very low base accelerations but also at very low frequencies. In order to choose the best candidate among all the PZTs found on the literature a selection process was made. The process consisted on simulating a device with a standard geometry and fixed base acceleration changing only the material. Then, for each material, the base excitation was forced to actuate in a range of frequencies and the electric circuit was studied for several load resistances. This method allowed the identification of the resonance frequency $f_r$ of the beam and the load resistance $R_l$ that optimizes the output results. There is another interesting frequency that shows a peak in the produced power: the anti-resonance frequency $f_{ar}$, the natural frequency of the device under open circuit conditions. The resistance load that maximizes the power at this frequency is called $R_{loc}$ $^3$. Similarly, the $f_r$ is the natural frequency associated to the device when short circuit conditions are applied. The optimal load resistance is called $R_{isc}$ (sc, referring to short-circuit).

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$^3$ Open-circuit load resistance
After the study, PZT 5J was found to be the best candidate to design the harvester. It is worth to mention that doped materials improve performance as stated before. However, since the aim of the project is to study a specific application to piezoelectric harvesters a deeper study of doped materials was not carried out.

The remaining analysis before the endurance evaluation concerns the size of the harvester. The dimensions of the piezoelectric beam must fit to the interior of the MAV. Maximum dimensions are critical since longer beams produce better results, but, then again, the devices are difficult to embed inside the vehicle. For the sake of the project aims, dimensions were chosen to take the maximum benefit of the piezoelectric effect, leaving to a later study on how to adjust the device into the MAV.

The maximum area allowed for the harvester has been set to 5% of the total MAV plain surface. For the used model, this percentage is equivalent to a maximum area of $A_{MAV_{max}} = 11.25 \, \text{cm}^2$. The dimensions of the harvester were then studied by a group of 9 different rectangular shaped harvesters with different aspect ratios. Thickness remained unchanged for all harvesters and no tip mass was added for these preliminary tests. For each harvester, performance simulations were made at the maximum allowed base excitation. Figure 3, shows that a large aspect ratio affects strongly the provided power and reduce the natural vibration of the beam. The higher the aspect ratio the higher the power and the lower the resonance frequency.

![Figure 3 Power provided by different shaped harvesters](image)

The addition of a tip mass was simulated for G1 harvester (highest aspect ratio) by choosing a mass with the same width dimension as the device and a changing longitude without surpassing the total harvester length. The results have shown that a 5mm long tip mass can be added, improving the power and maintaining the natural frequency. The maximum potential obtained for this condition is given in Table 3.

<table>
<thead>
<tr>
<th>Output parameters</th>
<th>$V_{P_{max}}$</th>
<th>$f$</th>
<th>$P_{density}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4.1</td>
<td>22.61</td>
<td>6.174</td>
</tr>
</tbody>
</table>

Finally the analysis of the endurance with the selected harvester showed that the mass addition cannot be compensated by the power of the harvester, typically leading to a 2-minutes reduction in the MAV endurance, as
shown in Figure 4. As a theoretical alternative, if the mass of the device was able to be part of the structure as well, then the endurance would be increased, but in such small amount that it cannot be accounted as an improvement.

![Figure 4 Endurance vs. mass of the MAV with added harvester](image)

**VI. Conclusions**

The analyses performed during this study were focused on the assessment of the electric power that a cantilever harvester can provide, when the device is installed inside a fixed-wing MAV structure. The objective was to use this energy as a primary recharging method to extend the endurance of such vehicles.

The results show that, with the current state of technology, piezoelectric materials cannot be a primary source for recharging the batteries of the propulsion system. The study of the excitations acting over the structure of an MAV (represented as a sinusoidal-leading-edge flying wing) revealed low accelerations acting at approximately 1-Hz frequencies. Those restrictions were considered when designing the cantilevered harvester leading to power outputs of a few $\text{mW}$ at about 20 Hz frequencies. Both tasks (reaching the goal excitation frequency and provide enough power to feed the batteries) were infructuous due to size limitation of the harvester and lack of higher excitations. The link between the geometrical shape of the beam and the natural frequency showed the major necessity of high aspect ratio dimensions but the size of the MAV reduce the length and width to a maximum amount that cannot be exceeded. Thus the area of the harvester is limited (as well as that of the piezoelectric material) and with the already mentioned excitations it is not currently possible to reach the desired output requirements. An external harvester configuration was also considered but research on literature showed similar outputs for devices placed in free streams with similar velocities those for the operation of MAVs. This fact and the complexity to build a code to simulate the behavior of a beam subjected to the air flow discouraged a deeper study of this approach.

The validation of the code used for the simulations along with a comparison of cantilever harvester studies ensures the solid results of the work. Even in larger scale aerial vehicles, such as small UAVs available studies show piezoelectricity is suitable only for secondary power sources, namely to feed electronics in the aerial vehicle. In order to avoid losing endurance the devices must have a multifunctional propose, so that the overall weigh is not increased.
References


