Piezoelectric energy harvesting from morphing wing motions for micro air vehicles

Abdessattar Abdelkefi¹, a) and Mehdi Ghommem²

¹) Department of Engineering Science and Mechanics, Virginia Tech, Blacksburg, Virginia 24061, USA
²) Center for Numerical Porous Media (NumPor), King Abdullah University of Science and Technology, Thuwal 23955-6900, Kingdom of Saudi Arabia

(Received 27 May 2013; accepted 30 July 2013; published online 10 September 2013)

Abstract Wing flapping and morphing can be very beneficial to managing the weight of micro air vehicles through coupling the aerodynamic forces with stability and control. In this letter, harvesting energy from the wing morphing is studied to power cameras, sensors, or communication devices of micro air vehicles and to aid in the management of their power. The aerodynamic loads on flapping wings are simulated using a three-dimensional unsteady vortex lattice method. Active wing shape morphing is considered to enhance the performance of the flapping motion. A gradient-based optimization algorithm is used to pinpoint the optimal kinematics maximizing the propellent efficiency. To benefit from the wing deformation, we place piezoelectric layers near the wing roots. Gauss law is used to estimate the electrical harvested power. We demonstrate that enough power can be generated to operate a camera. Numerical analysis shows the feasibility of exploiting wing morphing to harvest energy and improving the design and performance of micro air vehicles. © 2013 The Chinese Society of Theoretical and Applied Mechanics. [doi:10.1063/2.1305204]

Keywords energy harvesting, piezoelectric material, micro air vehicles, wing morphing

Micro air vehicles (MAVs) are small flying systems that are expected to be operated in urban environments and confined spaces (inside buildings, caves, or tunnels). To perform surveillance and intelligence missions, they are expected to carry sensors, cameras, and communication devices to receive and transmit data. In any successful design of MAVs, both weight and power budgets must be managed carefully. While most of the power supply is for the propulsion, power demand for operating the sensors and communication devices has to be considered. To meet the power requirements, one must equip MAVs with small batteries.¹,² The weight and energy storage limitations of these batteries impact significantly the performance of MAVs. As such, new technologies that enable energy harvesting from wing morphing would certainly enhance this performance. One advantage of flapping MAVs is the ability to integrate the aerodynamic loads with the vehicle’s stability and control. This integration is beneficial for managing the weight of vehicle. A recent study by Ghommem et al.³ showed that wing morphing significantly enhances the efficiency of the thrust power of flapping MAVs.

In this work, we study harvesting energy from wing morphing for small batteries, which can be a part of the power management and can be used to power sensors, cameras, or communication devices. To determine the amount of power that can be harvested from wing morphing, we simulate the aerodynamic loads on flapping wings and introduce active shape morphing to optimize the efficiency defined as the ratio of the propulsive power to the required aerodynamic power.³,⁴ Then, in order to convert the strain variation from the wing deformation to a usable source of energy, we attach piezoelectric layers to the morphing wings near their roots (Fig. 1). The piezoelectric layers are tied by two in-plane electrodes with negligible thickness connected to an electrical load resistance. We note that these layers are embedded in the flapping wings. Finally, we use Gauss law to relate the electrical part of the piezoelectric layer to the mechanical vibration of the flapping wing and hence determine the electrical harvested power. Furthermore, the load resistance effect and morphing frequency on the level of the harvested power are investigated.

Fig. 1. Schematic of the flexible flapping wing-based energy harvester. A piezoelectric patch is attached to the wing near its root to convert the strain variation from its deformation to a usable source of energy.

a)Corresponding author. Email: abdes09@vt.edu.
During the forward flight, the displacement of wing consists of one global motion (that means the wing moves as a whole), which is the flapping motion \( \phi(t) \), and two local motions (i.e., move spatially), which are the bending \( \gamma(\mathbf{X}, t) \) and twisting \( \beta(\mathbf{X}, t) \) motions. Following Ghommem et al., we express an arbitrary point’s position vector \( \mathbf{R}(\mathbf{X}_0, t) \) as

\[
\mathbf{R}(\mathbf{X}_0, t) = \mathbf{T}(\mathbf{X}_0 + \gamma^c(\mathbf{X}_0, t)\mathbf{e}_y + \gamma(\mathbf{X}_0, t)\mathbf{e}_z),
\]

where \( \gamma^c \) is the displacement along the spanwise direction which is introduced to ensure the wing length (from root to tip) does not change during the motion, \( \mathbf{T} \) is the transformation matrix that relates the moving frame to the fixed one, and \( \mathbf{X}_0 \) denotes the initial grid of wing defined under the global coordinate system. Over one cycle, the flapping motion is assumed to be harmonic; that is

\[
\phi(t) = A \sin(\omega t + \psi),
\]

where \( A \) is the flapping amplitude, \( \omega \) is the flapping frequency, and \( \psi \) is the phase angle. Furthermore, we propose a prescribed wing’s deformation using shapes of twisting and bending mode and it is defined as

\[
\gamma(\mathbf{X}_0, t) = \gamma(t) \cdot G(\mathbf{X}_0),
\]

\[
\beta(\mathbf{X}_0, t) = \beta(t) \cdot F(\mathbf{X}_0),
\]

and the spatial functions \( G \) and \( F \) are given by

\[
F(\mathbf{X}_0) = \mathbf{X}_0(2)/b^2/2, \quad \gamma(t) = \sin(2\pi t),
\]

\[
G(\mathbf{X}_0) = (\mathbf{X}_0/b)^2,
\]

where \( b \) is the wing span length. Further details of the wing kinematics implementation are provided by Ghommem et al. and Stanford and Beran. The temporal functions \( \gamma(t) \) and \( \beta(t) \) are defined using harmonic functions (similar to Eq. (2)). The imposition of the wing’s deformation is referred to as active shape morphing. From practical standpoint, this can be obtained by connecting the wing with simple torque rods driven by DC motors.

The aerodynamic loads of the flapping wings are simulated using a three-dimensional unsteady vortex lattice method (UVLM). Although comparing with other methods based on the Euler or Navier-Stokes functions, much less computation resources are required for, this UVLM method only applies to inviscid, incompressible flows in which the separation lines are known a priori. In spite of these restrictions, the use of UVLM remains adequate for the application of our interest. In this method, the boundary layers are approximated by a vorticity sheet consisted of two parts. The first part represents the lifting surface whose position is specified (wing kinematics as described above). It is called the bound vortex sheet and a pressure jump may exist across it. The second part represents the wake which deforms freely. It is called the free vortex sheet. The bound and free vortex sheets are joined along the sharp edges where separation occurs and the Kutta condition is imposed (as shown in Fig. 2). As for numerical simulation, the entire bound and free vortex sheets are replaced with discrete vortex rings. Every vortex ring consists of four straight short vortex segments. The result shows the body surface is dividing by a lattice of vortex lines into elements. The vorticity circulation on the lifting surface is obtained by employing the Biot–Savart law that computes the velocity induced by a vortex segment and imposing the no-penetration condition at each element of the surface. Figure 2 depicts the flapping wing and its associated wake where the color levels denote the vorticity circulation strength. The vorticity in the wake was generated on and shed from the wing at an earlier time. Pockets of highest circulation are observed in the wake of the flapping wings during the downstroke. Finally, ones can use the unsteady Bernoulli equation to determine the corresponding aerodynamic loads and pressure distribution. Further details on the current implementation of the UVLM solver along with validation and verification studies are provided by Ghommem et al.

Next, we combine UVLM with a globally convergent method of moving asymptotes to determine the optimal kinematics (bending and twisting motions) that maximize the propulsive efficiency \( \eta \), which is defined as the ratio of the propulsive power over the aerodynamic power. This optimization technique is a gradient-based method and employs conservative convex separable approximations to solve inequality-constrained nonlinear programming problems. This method performs the search for the optimal configuration by producing approximate subproblems at each iteration, in which the objective and constraints functions are replaced by certain convex functions. More details on this algorithm can be found in Refs. 6 and 7.

Results are presented for a cambered rectangular wing with an aspect ratio of 6 and chord length \( c = 5 \) cm. We consider the case when the flapping, bending, and twisting frequencies are equal. Furthermore,
we assume that the piezoelectric patches used to harvest energy are part of the structure of the wing. Several optimization runs are conducted with a flapping angle equal to 45° and different reduced frequencies. It is noted that the bending and twisting are considered to be limited by ±0.7ε and ±25°, respectively. The optimized results are presented in Table 1 for the reduced frequencies κ = 0.075, 0.1, and 0.125. We note that the reduced frequency is calculated as κ = ω/U∞c/2, where the flight speed U∞ is set to 0.5 m/s. It is clear that morphing the wing through a combination of twisting and bending yields an increase in the propulsive efficiency. This increase is mainly due to a decrease in the input aerodynamic power with respect to the baseline case. We observe that increasing the reduced frequency κ enables better performance in terms of propulsive efficiency but requires more aerodynamic power. This is expected since increasing κ leads to higher angular acceleration for the wing and consequently for the surrounding fluid (non-circulatory or added mass effects) which would require additional amount of power to accelerate the surrounding fluid.

Table 1. Optimal results for κ = 0.075, 0.1, and 0.125.

<table>
<thead>
<tr>
<th>Wing morphing</th>
<th>κ</th>
<th>C_L</th>
<th>C_T</th>
<th>P_{Aero}/W</th>
<th>η</th>
<th>Optimal solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>No morphing</td>
<td>0.075</td>
<td>0.687</td>
<td>0.00446</td>
<td>1.48 × 10^{-4}</td>
<td>0.0345</td>
<td>—</td>
</tr>
<tr>
<td>Bending and twisting</td>
<td>0.075</td>
<td>0.687</td>
<td>0.01070</td>
<td>1.81 × 10^{-4}</td>
<td>0.0676</td>
<td>γ(t) = 0.7πsin(1.5t − 1.59)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>β(t) = 8.133πsin(1.5t − 0.9)</td>
</tr>
<tr>
<td>No morphing</td>
<td>0.1</td>
<td>0.695</td>
<td>0.03275</td>
<td>1.97 × 10^{-4}</td>
<td>0.191</td>
<td>—</td>
</tr>
<tr>
<td>Bending and twisting</td>
<td>0.1</td>
<td>0.695</td>
<td>0.03400</td>
<td>1.80 × 10^{-4}</td>
<td>0.216</td>
<td>γ(t) = 0.7πsin(2t − 1.59)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>β(t) = 6.95πsin(2t + 0.225)</td>
</tr>
<tr>
<td>No morphing</td>
<td>0.125</td>
<td>0.706</td>
<td>0.06742</td>
<td>2.63 × 10^{-4}</td>
<td>0.299</td>
<td>—</td>
</tr>
<tr>
<td>Bending and twisting</td>
<td>0.125</td>
<td>0.706</td>
<td>0.05673</td>
<td>1.83 × 10^{-4}</td>
<td>0.355</td>
<td>γ(t) = 0.7πsin(2.5t − 1.59)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>β(t) = 11.67πsin(2.5t + 0.78)</td>
</tr>
</tbody>
</table>

where ε_{33} represents the coefficient of piezoelectric stress, ε_{33} denotes the permittivity under constant strain, ε_{11} is the bending strain, the electric field E_3(t) = − V(t)/h_p is defined in the poling direction, and V(t) represents the voltage between the piezoelectric electrodes, as the potential of the upper electrode. The general form of the electromechanical coupling equation is given by

\[ C_p \dot{V} + \frac{V}{R} + \theta \dot{\gamma} = 0, \]

(7)

where C_p is the equivalent capacitance of the piezoelectric layer which is directly related to the permittivity at constant strain ε_{33}, and θ is the electromechanical coupling term which is directly related to the piezoelectric stress coefficient ε_{13}. The values of the capacitance C_p and electromechanical coupling θ are set to 120 nF and 1.55 mN/V, respectively.

The voltage and harvested power are determined by solving Eq. (7) for the optimized morphing configurations as reported in Table 1. For a harmonic oscillation with a frequency ω of the temporal bending motion, we express the generated voltage (V) and the temporal bending motion (γ) in Eq. (7) in a complex form. Using this methodology, the expressions of the maximum generated voltage \( V_{\text{max}} \) and maximum harvested power \( P_{\text{hmax}} \) are given by

\[ V_{\text{max}} = \frac{\theta \omega R_{\text{max}}}{\sqrt{1 + C_p^2 \omega^2 R^2}}, \]

\[ P_{\text{hmax}} = \frac{V_{\text{max}}^2}{R} = \frac{\theta^2 \omega^2 R_{\text{max}}^2}{1 + C_p^2 \omega^2 R^2}. \]

(8)

Table 2 shows the effects of varying the reduced flapping frequency κ on the piezoelectric harvested power for the optimized morphing configurations. We note that, for the baseline configurations (no morphing), the piezoelectric harvested power is always zero. This is due to the absence of strain variation on the wing.
Table 2. Variation of the harvested power $P_h$ with the bending reduced frequency $\kappa$ for the optimized morphing configurations. The electrical load resistance $R$ is set to $10^6$ $\Omega$.

<table>
<thead>
<tr>
<th>$\kappa$</th>
<th>$P_h$/$W$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.075</td>
<td>$6.41 \times 10^{-3}$</td>
</tr>
<tr>
<td>0.1</td>
<td>$1.1 \times 10^{-2}$</td>
</tr>
<tr>
<td>0.125</td>
<td>$1.7 \times 10^{-2}$</td>
</tr>
</tbody>
</table>

We observe that the piezoelectric harvested power with $R = 10^6$ $\Omega$ is enough to roughly cover the required power for operating onboard devices, such as a camera, which is estimated to be around 50 mW as reported in Ref. 15.

![Figure 3](image_url)  

**Figure 3.** Variation of the harvested power with the load resistance for different optimized configuration when varying the bending frequency $\omega$. Results are presented with dimensional quantities.

Figure 3 shows the effect of the electrical load resistance on the harvested power when varying the bending frequency $\omega$. We observe that increasing the bending frequency yields an increase in the harvested power when the electrical load resistance is lower than $10^7$ $\Omega$. In fact, the optimizer identified the same bending amplitude (upper bound) for all optimized cases, as shown in Table 1. Consequently, only the bending frequency and the electrical load resistance affect the generated voltage and harvested power, as shown in the expressions of maximum voltage and power (Eq. (8)). Furthermore, it is noted that an optimum value exists for the electrical load resistance that maximizes the harvest energy for each value of the bending frequency $\omega$. This optimal value depends on the capacitance of the harvester and the bending frequency and is equal to $1/(C_p \omega)$. For the considered values of bending frequencies (2.5 rad/s, 2 rad/s, and 1.5 rad/s), the optimum values of the electrical load resistance are equal to $3.33 \times 10^6$, $4.17 \times 10^6$, and $5.55 \times 10^6$ $\Omega$, respectively.