

A Flapping Airflow Energy Harvester with Flexible Wing Sections

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Abstract

This paper reports a novel method to improve output power of a flapping airflow energy harvester by introducing flexible wing sections. The flapping airflow energy harvester consists of a cantilever beam structure with a wing at its free end. A bluff body is placed in front of the wing to induce aerodynamic instability that leads to up and down oscillation of the wing. By coupling transducers to the oscillating wing, electromagnetic in this case, electrical energy can be generated. In this research, instead of using a commonly used rigid wing, the proposed airflow energy harvester has flexible wing sections that are able to bend, thus reduce the aerodynamic resistance during the wing oscillation. Therefore, the overall mechanical damping can be reduced and output power of the proposed energy harvester is increased. It is found experimentally that the proposed method is able to improve energy harvester performance of flapping airflow energy harvesters under high airflow speeds.

Introduction

Flapping energy harvesters are promising options for energy extraction from flow induced vibrations as they typically benefit from vortex shedding, flutter or wake of bluff body and are able to achieve reasonable output power in low speed flow environments [1][2]. They also have longer lifespan and require less maintenance compared to wind turbines. Different vortex/wake energy harvesters combined with a cantilever-beam and flapping foils/wings are usually applied in the design of such harvesters [1][3-7].

This study focuses on a specific type of flapping airflow energy harvesters that typically have a wing with a relatively large area to generate sufficient lift force to initiate the wing oscillation [8-10]. The large area rigid wing in this type of flapping airflow energy harvester, however, will encounter high aerodynamic resistance. As a result, they have higher mechanical damping during its oscillation, which reduces output power of such energy harvesters. Progresses have been made to improve performance of such energy harvesters by using external mechanical interventions [9].

This paper will introduce a new method to improve performance of a flapping harvester based on rigid wings and electromagnetic conversion [8-11] by applying flexible wing sections to the original design. Flexible wings are usually applied on micro air vehicles at low Reynolds number (10^3 - 10^5) for improved aerodynamic efficiency, better lifting and thrusting forces [12-14]. The bio-inspired wing designs can be very complicated (e.g. a combination of skeleton and flexible sections [13]) and need to provide enough thrust and stability in a fluctuating low Reynolds number environment [12-18]. The operation principle of the proposed method will first be introduced followed by experimental verification and conclusions.

Principle

The original flapping airflow energy harvester that this study is based on consists of a cantilever beam structure with a wing at its free end as shown in Fig 1. Details of this device can be found in [8]. The flapping airflow energy harvester consists of a cantilever beam structure with a wing at its free end. A bluff body is placed in front of the wing to induce aerodynamic instability that leads to up and down oscillation of the wing. By coupling transducers to the oscillating wing, electromagnetic in this case, electrical energy can be generated.

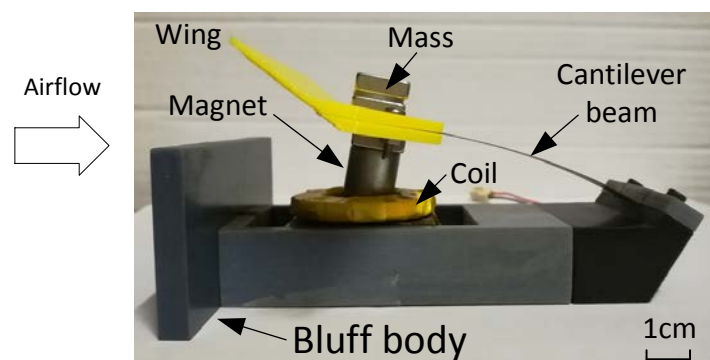


Fig. 1. Side view of a flapping airflow energy harvester.

As mentioned above, the large wing leads to high aerodynamic resistance and mechanical damping during its operation, which reduces output power of such an energy harvester. In order to address this problem while maintaining the required lift force, this research proposes to introduce flexible wing sections as shown in Fig 2(a). Comparing to the rigid wing as shown in Fig 2(b), the rigid area is reduced along the wing span and the removed area is replaced with flexible sections. The two flexible sections are attached to a small rigid section in the centre of the wing. Both flexible sections can move freely along the thickness of the wing. Fig 3 illustrates the top view of the wing with flexible sections.

The operational principle of the proposed method is as follows: when the wing move downwards, the two flexible wing sections bend upwards. This reduces the effective wing area that meets the air and facilitates airflow to flow around the wing as shown in Fig 4(a), both of which help reduce the aerodynamic resistance and mechanical damping of the wing structure. When the wing move upwards, the two flexible wing sections bend downwards, which has the same effects of reducing mechanical damping.

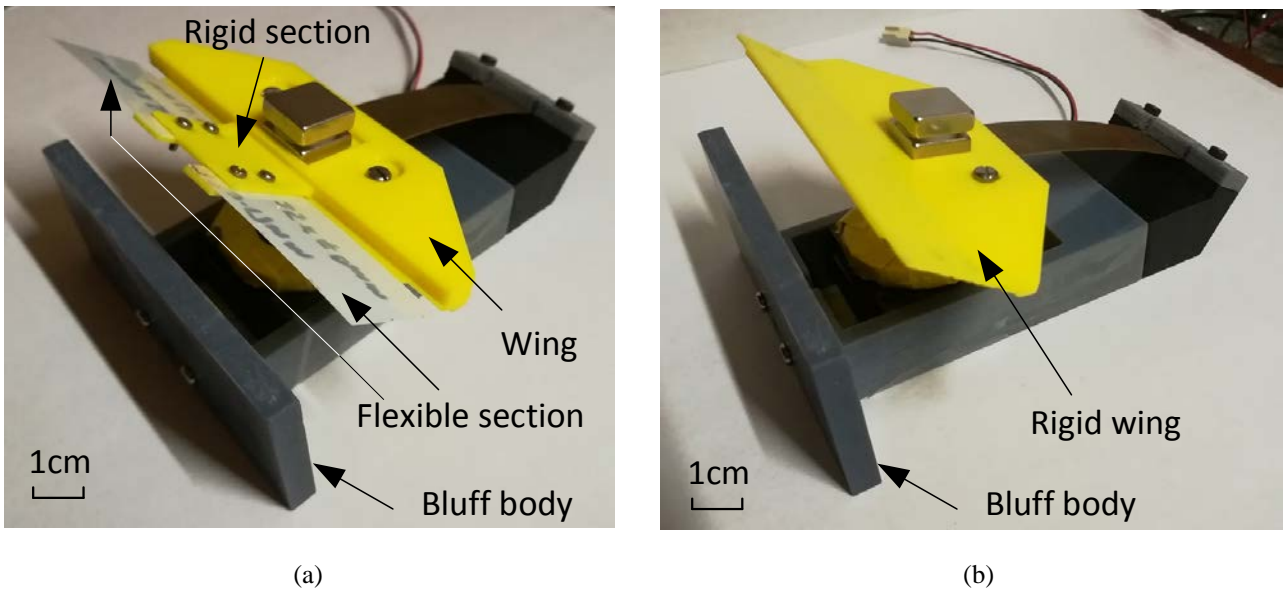


Fig 2. (a) A flapping airflow energy harvester with flexible wing sections. (b) A flapping airflow energy harvester with a rigid wing.

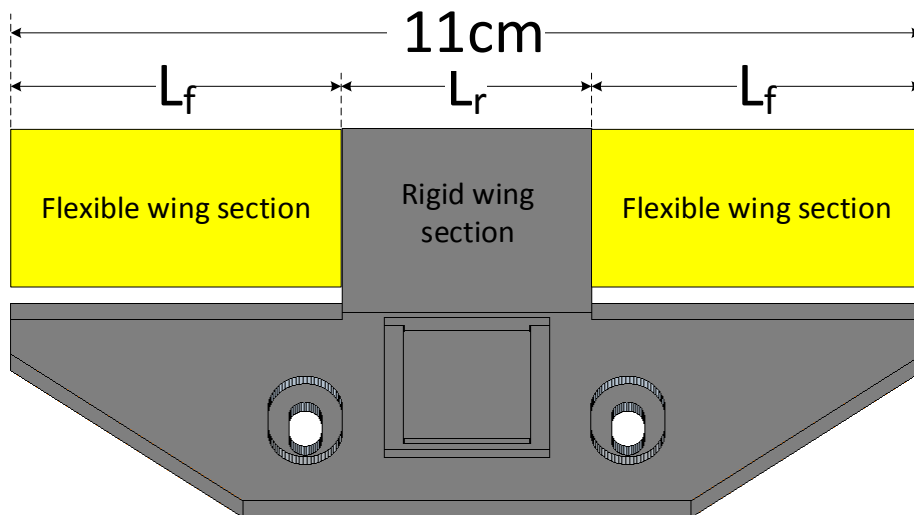


Fig. 3. Top view of the proposed wing with flexible sections.

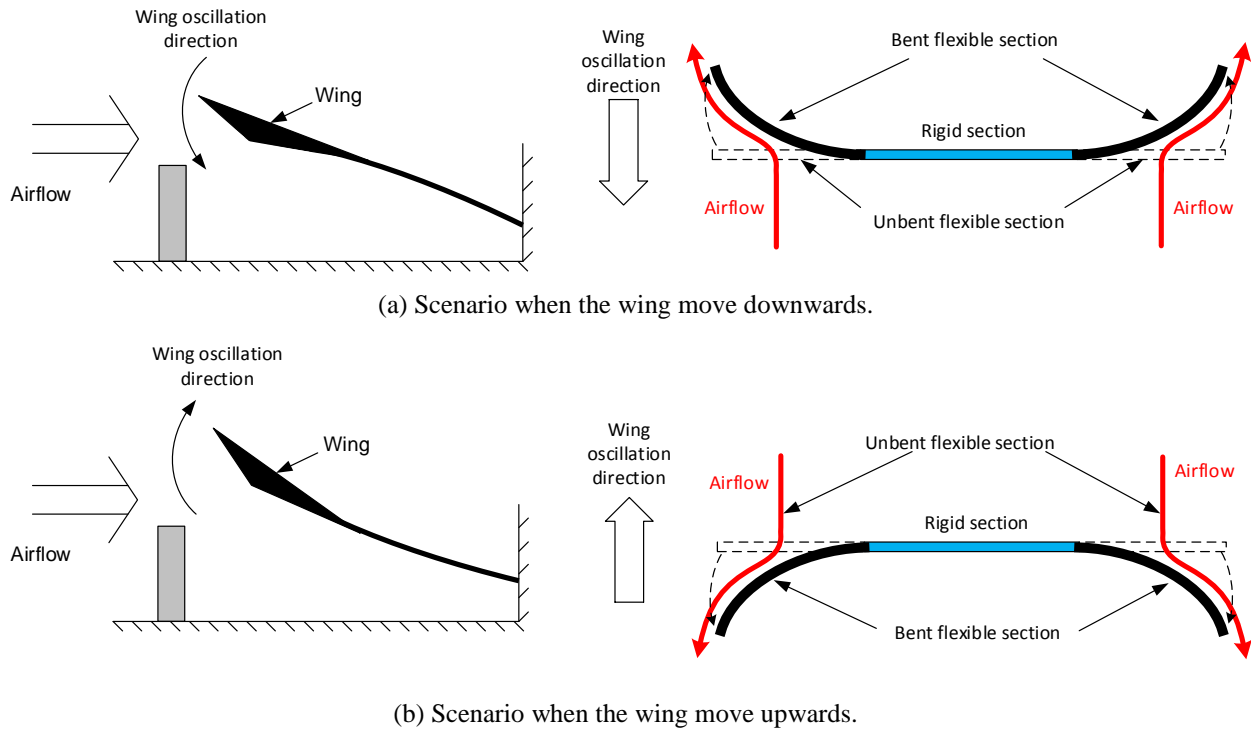


Fig. 4. Conceptual view of the bending flexible sections during wing oscillation (left: side view, right: front view).

Experiment

In order to prove this theory, a prototype energy harvester with flexible wing sections on both ends of the wing as shown in Fig 2(a) were built, tested and compared with a benchmark prototype that has a rigid wing as shown in Fig 2(b). The total width of the wing was fixed to 11 cm for all prototypes. Flexible sections are made of BoPET (biaxially-oriented polyethylene terephthalate, also known as Mylar with Young's modulus $E = 490 \text{ MPa}$ and mass density $\rho = 1.39 \text{ g cm}^{-3}$). Flexible sections with different lengths, L_f (3 cm, 4 cm and 5 cm) and thicknesses (100 μm , 170 μm , 240 μm and 300 μm) were investigated. The cantilever beam is made of BeCu and has dimensions of 0.3 x 20 x 60 mm. Total mass of all wing prototypes were fixed at 77.9 g. All prototypes were tested in a wind tunnel under airflow speeds between 2.5 $\text{m}\cdot\text{s}^{-1}$ and 9.157 $\text{m}\cdot\text{s}^{-1}$ (Corresponding Reynolds numbers are between 8107 and 29698).

Each prototype was tested with the resistive load ranging from approximately 1 $\text{k}\Omega$ to 400 $\text{k}\Omega$. The optimal loads are influenced by system damping and dependent of wind velocity and wing design [9]. The maximum power at optimum loads was used to evaluate the improvement of flexible wing design on power output.

Fig 5 shows experimental results when the flexible section lengths, L_f , varies from 3 cm to 5 cm. It was found that in general, when the airflow speed is low ($< 5.5 \text{ m}\cdot\text{s}^{-1}$), output power of prototypes with flexible wing sections are similar to or lower than the benchmark prototype with a rigid wing. When the flow speed is high ($> 5.5 \text{ m}\cdot\text{s}^{-1}$), prototypes with flexible wing sections outperform the benchmark prototype.

At high airflow speeds, length and thickness of the flexible section have noticeable impact on output power of the energy harvester. For 3 cm long flexible section the 170 μm thick case has the best performance. When the flexible section is 4 cm long, the 240 μm case has the maximum power output. When the section is further increased to 50 mm, the four cases have similar performance.

It was also observed in the experiment that at low airflow speed, the flexible sections had self-oscillation and did not bend as described in the previous section. Therefore, the energy harvester with flexible section could not perform as predicted in hypothesis and thus have lower output power than the energy harvester with rigid wing. When the airflow speed increases, the self-oscillation on flexible sections became less obvious and they performed in a way as predicted in hypothesis. As a result, its aerodynamic resistance and thus mechanical damping was reduced, and hence, higher output power was achieved.

It is worth mentioning that when the flexible section is 3 cm long and 300 μm thick, output power becomes lower than the rigid wing case at high airflow speed. This is mainly because that the flexible section in this case is not flexible enough to bend to a degree that facilitates the airflow to flow around the wing. In

addition, the self-oscillation of the flexible section in this case becomes a dominant factor even under the high airflow speed, which introduces extra mechanical damping to the wing structure and thus reduces output power of the energy harvester.

In addition, vortex is produced around the tips of the wing. Flexible tips are more likely to be affected by such vortices which help the flexible wing sections bend. Such effect becomes more noticeable especially at higher airflow speed. Vortex shedding and vortices could be generated during the flapping process [14][19][20] and all of these contribute to aerodynamic efficiency and power improvement. This also explains why flexible wings behaves better than rigid wings at higher airflow speed in most cases.

Furthermore, at the same flexible wing thickness, prototypes with longer flexible wing sections have higher output power. This is because longer wing sections can bend more under same load conditions and thus lead to lower mechanical damping.

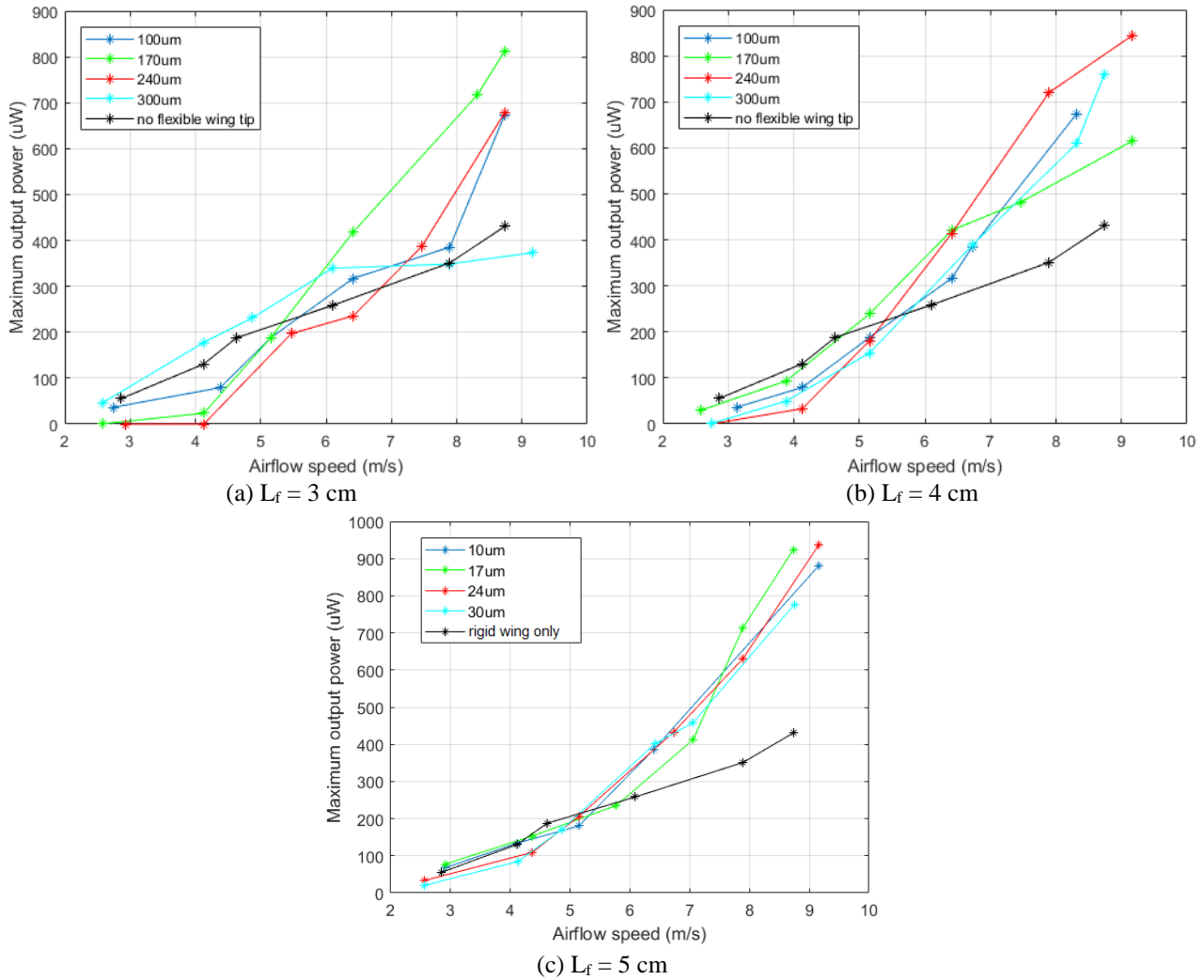


Fig. 5. Comparisons of maximum output power of the flapping airflow energy harvesters with and without flexible wing sections at various lengths of the flexible section, L_f .

Conclusions

This paper presents a novel method of introducing flexible wing sections on a flapping airflow energy harvester to improve its output power, especially under high airflow speeds. The method was experimentally verified. It is concluded that flexibility of the additional wing section plays an important role in performance of the energy harvester. If the wing section is too flexible, there is not sufficient lift force that limits the oscillation amplitude of the wing structure and thus the output power. On the other hand, if the wing section is too rigid, it cannot bend sufficiently to allow air to flow around the wing, which neutralise the benefit of the flexible wing. Furthermore, self-oscillation on relatively rigid flexible wing section could even reduce the output power, which must be minimised when designing such structures.

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