Modeling and experimental characterization of a fluttering windbelt for energy harvesting

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Abstract. Wind energy harvesters based on fluttering offer a valuable and efficient alternative to the traditional wind turbines. A longer life expectancy and cheaper fabrication is attained through the absence of gears or bearings. This article presents the theoretical and experimental study of a novel windbelt-based energy harvester, designed to harvest from continuously changing low-speed winds. A theoretical model is derived to explore the scaling effect on the critical flutter frequency, and experimental results validate the theoretical predictions.

1. Introduction
Aeroelastic flutter is a self-feeding vibration of an elastic structure in a fluid flow. It occurs from a flutter limit wind speed, when there is a positive feedback between the structure natural vibration and the aerodynamic forces exerted by the fluid flow, leading to a large amplitude of vibration only limited by the mechanical and aerodynamic damping. Although fluttering is usually considered as a destructive phenomenon, it has been recently demonstrated that the self-feeding vibration of a membrane or a cantilever can be used with a piezoelectric [1, 2] or an electromagnetic device to harvest energy from wind. A few micro and macro-scales prototypes have been demonstrated [3, 4], and the company Humdinger Wind Energy [5] commercializes a small device harvesting 2.2 mW AC at a wind of 6 ms⁻¹. An experimental characterization of a Humdinger windbelt of 50 cm length has been performed by Pimentel et al. [6] to study the influence of the tension and the wind angle of attack on the harvested power. The latter is the only published work focusing on the windbelt optimization. The present paper aims at extending this study by providing tools for the optimization of a flutter-based energy harvester. A theoretical model is derived from Theodorsen flutter theory [7] and allows the simulation of the flutter frequency and critical wind speed evolution as a function of the ribbon parameters. An experimental analysis completes the results.

2. Prototype and optimization objectives
The proposed prototype is an omnidirectional wind energy harvester suitable for the low-speed and omni-directional winds of Singapore [8]. It consists of four ribbons separated by 45 degrees accelerating walls (figure 1). Each ribbon exploits the flutter phenomenon to convert the wind energy into mechanical vibrations. This mechanical energy is then in turn transformed into electrical energy with an electromagnetic generator: when a light copper coil attached to the fluttering ribbon moves within the static electromagnetic field generated by a fixed magnetic circuit with permanent magnets, a voltage is generated across the coil ends according
Fluttering windbelt
Usable electrical energy
Wind energy
Non usable electrical energy
Mechanical vibration energy
Electromagnetic transducer
Electrical extraction circuit
Usable electrical energy

Figure 1. Schematic of the prototype.

Figure 2. Structure of the energy harvester.

to Faraday’s law of induction (figure 2). Finally, an energy extraction circuit is needed to rectify
and adjust the generated voltages in order to supply a load.

Optimization of this harvester can be approached in three directions:

- **Maximizing the harvested power.** Previous studies have shown that maximizing
the power generated by an electromagnetic generator can be reached by improving the
electromechanical coupling coefficient and reducing the electromagnetic generator losses
coefficient (reducing the coil resistance for instance). Another more obvious way is to
increase the input vibration acceleration [9]. Thus from an aerodynamic viewpoint only,
optimizing the fluttering ribbon will aim at getting the maximum vibration acceleration.
This optimization has been experimentally studied in a previous work [8].

- **Maximizing the power density.** This can also be seen as minimizing the size. In
our case, reducing the harvester size mainly means reducing the ribbon length which is
much bulkier than the electromagnetic device itself. The effect of scaling the ribbon is
theoretically studied in section .

- **Enlarging the range of wind speeds at which it is harvesting energy.** This
aim can be translated as reducing the minimal wind speed at which the flutter starts. In
this objective, the critical flutter wind speed will be studied as a function of several design
parameters.

3. **Theoretical results**

3.1. **Model of the fluttering ribbon**

We consider a thin and long ribbon clamped at both ends, and pre-strained by a tension force
$T$. The ribbon is subjected to an incompressible fluid flow of speed $U$. When this velocity
reaches the flutter critical velocity $U_c$, a self-sustained dynamic oscillation of large amplitude
and stable frequency $f_c$ occurs (figure 3). The model comprises a finite elements modal analysis
performed with the ANSYS software, which determines the first uncoupled heaving and torsion
modes frequencies. The second part of the program is a two-dimensional, two degrees of freedom
model based on Theodorsen flutter theory [7, 10]. The modal resolution of the coupled heaving
and torsion mode gives an estimation of the coupled flutter frequency $f_c$ as well as the critical
wind speed $U_c$ (figure 4). The mass repartition is supposed symmetrical, and this model does
not take into account the effect of concentrated masses.

3.2. **Theoretical results**

The ribbon dimensions and characteristics are summed up in table 1. The simulation results
show that for these parameters the flutter frequency varies between 10 and 70 Hz, depending on
the tension $T$. The limit wind speed varies between 1 and 6.4 m/s. At a tension of 0.5 N, the
Figure 3. Windbelt and notations, before and after the critical wind speed.

| Value       |         |
|-------------|---------|
| B           | 0.013 m |
| L           | 0.450 m |
| W           | $15 \times 10^{-6}$ m |
| T           | 0.5 N   |
| d           | 1779 kg/m$^3$ |
| E           | $2.51 \times 10^9$ Pa |
| Poi         | 0.23    |
| m           | $0.35 \times 10^{-3}$ kg/m |

Table 1. Windbelt parameters.

Figure 4. Schematic of the fluttering model.

calculated frequency is 31 Hz and the critical wind speed is 2.5 m/s, which seems suitable for our application targeting low wind speeds.

When the ribbon tension is varied from 0.1 to 3 N, the figure 5 shows the evolution of $U_c$ and $f_c$ as a function of $T$, for several lengths $L$. The frequency is, as expected, an increasing function of the tension, as is the flutter limit speed. Both increase as well when the ribbon length is decreased.

If all the ribbon dimensions are scaled by a factor $s$ the model predicts an increase of the critical wind speed together with an increase of the flutter frequency with the miniaturization, as shown in figure 6. Note that $U_c$ is increasing at a faster rate when the length only is reduced. So when miniaturizing such a system, one should reduce the width and thickness at least at the same rate as the length.

4. Experimental measurements

A PET ribbon of same dimensions and parameters as the simulation is vertically tensed between one force sensor on the top and a stepper motor on the bottom (figure 7). The force sensor retrieves the tension of the ribbon and this information is used to control the stepper motor and
adjust the tension to the desired value. This setup allows to get a fixed and reproducible tension of the membrane. A mass, in this case two symmetric wound coils, is fixed on the ribbon close to the top edge. A laser displacement sensor pointing towards the coil is used to measure its vibration amplitude and frequency.

The first measurements are performed with two 0.5 g coils attached symmetrically on top of the ribbon. As expected, there is a minimal wind speed at which the flutter starts. As an example, figure 8 shows the vibration amplitude respectively before and after the flutter limit in one random case when the tension is low. The critical wind speed at 0.5 N is measured between 1 and 2 m/s, and the recorded flutter frequency is 30 Hz at low wind speeds. These values correspond well to the theoretical values calculated in section 2.

The figure 9 shows the flutter frequency as a function of the wind speed when the tension is varied from 0.5 to 3 N. Contrary to the theoretical results, the flutter frequency slightly increases with the wind speed. It also increases with the ribbon tension, accordingly with the theoretical results previously shown in figure 5. Another point is that the more tensioned the ribbon, the higher the wind speed necessary to induce flutter. This too corresponds to the theoretical results.

When the ribbon length is decreased from 45 cm to 25 cm, the critical wind speed increases.
as shown by figure 10, accordingly with the theoretical results presented in section 3. The discrepancies between the theoretical and experimental results might be due to the difficulty to measure $U_c$ in some cases, probably because of the not perfect balance of the two hand-wound coils.

5. Conclusion

This work presents two tools developed to help designing a windbelt-based energy harvester made of a fluttering ribbon and an electromagnetic transducer: a theoretical model and an experimental setup are used to give an estimation of the two characteristic parameters of the aerodynamic subsystem – the critical flutter frequency and the critical wind speed – as a function of the ribbon dimensions and the material properties. Simulation and experimental results notably show that the critical speed increases when the dimensions are scaled down. Thus in order to target low-speed winds, this increase has to be compensated by slightly reducing the ribbon tension for instance. Further works will focus on including the electromechanical subsystem and on studying the influence of the electromechanical coupling on the critical flutter frequency, in order to develop a global model of the harvester.

References

[1] Kwon S D 2010 Applied Physics Letters 97 164102 ISSN 00036951
[2] Li S, Xian S, Yuan J and Lipson H 2011 Journal of Applied Physics 109 026104 – 026104–3
[3] Kim S H, Ji C H, Galle P, Herrault F, Wu X, Lee J H, Choi C A and Allen M G 2009 Journal of Micromechanics and Microengineering 19 094010 ISSN 0960-1317
[4] Fei F, Mai J D and Li W J 2012 Sensors and Actuators A: Physical 173 163–171 ISSN 09244247
[5] Frayne S Humdinger Wind Energy URL http://www.humdingerwind.com
[6] Pimentel D, Musilek P, Knight a and Heckenbergerova J 2010 2010 9th International Conference on Environment and Electrical Engineering 81–84
[7] Theodorsen T 1935 General Theory of Aerodynamic instability and the mechanism of flutter Tech. Rep. NACA TR 496
[8] Arroyo E, Foong S, Marechal L and Wood K L 2014 Proceedings of the ASME 2014 Dynamic asystems and control conference pp 2–6
[9] Arroyo E, Badel a and Formosa F 2013 Journal of Intelligent Material Systems and Structures 24 2023–2035 ISSN 1045-389X
[10] Turnock D L 1985 Two degree of freedom flutter solution for a personal computer Tech. Rep. NASA Technical Memorandum 86381