Energy for Sustainable Development 33 (2016) 75–83

Contents lists available at ScienceDirect

Energy for Sustainable Development

Wind tunnel and initial field tests of a micro generator powered by fluid-induced flutter

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ARTICLE INFO

Article history:
Received 2 October 2015
Revised 26 February 2016
Accepted 20 April 2016
Available online xxxx

Keywords:
Aeroelasticity
Flutter
Micro wind energy

ABSTRACT

Aeroelastic flutter is a self-oscillating phenomenon resulting from interaction between a structure and the surrounding flow. This is well-known as a destructive phenomenon. However, it can also be used as a powerful mechanism to harvest wind energy at the scales and costs beyond the reach of turbines. Windbelt is a micro generator exploiting wind energy with small size and capacity, which was invented and developed a few years ago (Humdinger wind energy LLC, 2007) basing on aeroelastic flutter. The aim of this paper is to investigate the influences of the design parameters on the performance of a windbelt with the goal of maximizing its output power. An experimental apparatus is developed to study the effects of parameters such as wind speed, position and size of the magnets, pre-applied tension of the membrane, angle of attack of the membrane, and the direction of the generator on the output power and frequency of the windbelt. The experimental tests are carried out in a subsonic wind tunnel. After that, we deduce optimal parameters from experimental results to maximize the output power. Two micro generators are then fabricated and tested in both wind tunnel and real condition. The results show that a single micro generator (windbelt) can generate a power of from 3 to 5 mW and a windpanel of 5 single windbelts (larger ones) can generate a power of from 30 to 100 mW at the wind speed of less than 8 m/s. This output is sufficient to power many micro devices such as wireless sensors, electronic chips, LEDs, and cell phone chargers. Therefore, this micro wind energy generator may be widely used in practice.

Introduction

Wind energy is the kinetic energy of the air moving in the Earth's atmosphere (Hughes, 2012) and man has taken advantage of this kind of energy for thousands of years (Kalmikov and Dykes, 2010). After the oil crisis in the '70s, the study of energy production from alternative sources of energy has been enhanced around the world (Japan Center for Economic Research (JCER), 2012). These sources include but not are limited to wind energy, which has been considered as a clean and inexhaustible source. After the invention of electricity and electric generator, the idea of using wind energy to generate electricity soon came into being.

The most common way to harvest wind energy is rotating a turbine generator. However, wind turbines or windmills only work well for large-scale applications. Micro wind turbine, which is the smallest-sized wind turbine in the market, has a rotor diameter of from 0.5 to 1.25 m (Gipe, 2009) and the power of from 20 to 100 kW. They are still quite large for some applications such as charging battery and powering sensors. Also, wind turbine is very expensive and costly to manufacture, maintain, and repair. It also needs a very large space for installation. In addition, wind turbine may cause noise pollution, problems with television reception, or interference to radar installations (Pedersena and Waye, 2004). In fact, in the market, there still exist demands for a milliwatt-sized wind generator which is small, simple, and cheap.

Recently, some micro wind energy harvesting devices have been developed. Allen and Smits (2001) investigated the feasibility of placing a piezoelectric membrane in the wake of a bluff body and using the induced Von Karman vortices formed behind the bluff body to induce the oscillations of the membrane which generate an output power. Bryant and Garcia (2011) investigated a novel piezoelectric energy-harvesting device driven by aeroelastic flutter vibrations of a simple pin-connected flap and beam. A maximum power output of 2.2 mW at the flow velocity of about 8 m/s was reported. Sirohi and Mahadik (2009) tested a device that uses a galloping D-shaped beam exciting a PZT piezoelectric beam. It is reported that a maximum power output of 1.14 mW was achieved. Li et al. (2011) proposed and investigated a bio-inspired piezo-leaf architecture which converts wind energy into electrical energy by wind-induced fluttering motion. A series of experiments demonstrated a peak output power of approximately 0.6 mW and maximum power density of approximately 2 mW/cm^3 from a single leaf. Other works on micro wind energy harvester can be found in Tang et al. (2009), Erturk et al. (2010), and Bibo et al. (2011).

In 2007, S. Frayne developed a non-turbine or non-rotary wind energy harvesting device called windbelt, known as an aeroelastic instability

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http://dx.doi.org/10.1016/j.esd.2016.04.003
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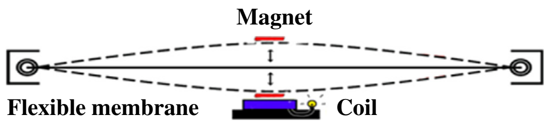

Fig. 1. Principle of operation of windbelt.

energy harvester (AIEH) (Humdinger wind energy LLC, 2007). A windbelt often has three components (Fig. 1): flexible membrane fixed at two ends subject to elastic oscillation, a magnet, and a coil. As the air flows through the membrane at sufficiently high speed, the flutter phenomena happens (Lombard, 1939) and the membrane oscillates. If the magnet is attached to the membrane, it oscillates accordingly. When the coil is put near the magnet, variable magnetic flux will appear through the coil to generate induction electricity in accordance with electromagnetic induction law of Faraday. This device has a typical cut in wind speed of around 2.7 m/s and a peak power output of ~5 mW (Humdinger wind energy LLC, 2007).

Among micro wind energy harvester cited above, windbelt expressed several advantages such as small size, inexpensive, no requirement of high manufacture technology or special materials, easy to repair and maintain, and generating higher output power. However, it is a new development and still has many areas which can be improved upon. There is also a need to make the process of manufacturing more standardized.

The aims of this paper are

- firstly, to investigate experimentally the effects of some parameters such as wind speed, position and size of the magnets, pre-applied tension and angle of attack of the membrane and the direction of the generator on
  + oscillating frequency of the membrane,
  + operational ability of the windbelt;
- secondly, to design and fabricate a windbelt model using optimal parameters deduced from experimental results; and
- finally, to test the fabricated windbelt in both wind tunnel and real wind condition and estimate its output power in order to draw out its potential applications.

Experiment

Test model

The operation of the windbelt is mainly subjected to the oscillation of the flexible membrane. However, the oscillation is affected by a lot of factors which are hardly pre-measured theoretically. Therefore, in order to characterize the performance of the windbelt, we used an experimental method. The main factors which can affect the operational ability of the windbelt are

- pre-applied tension of the membrane,
- angle of attack of the membrane,
- direction of the windbelt,
- position of the magnet, and
- size of the magnet.

In order to investigate the influences of all above factors on the operational ability of the generator, a test model was designed and fabricated as demonstrated in Fig. 2. The main characteristics of the test model are presented in Table 1.

The test model consists of four main components, including

(1) coil: a coil of 2500 rounds of 0.12 mm diameter copper;
(2) magnet: circular-shaped permanent magnet with 10 mm of diameter and 1.5 mm of thickness;
(3) flexible membrane: ripstop nylon fabric (one type of kite fabric) with 10 mm of width and 350 mm of length; and
(4) support: made of 3 mm plywood.

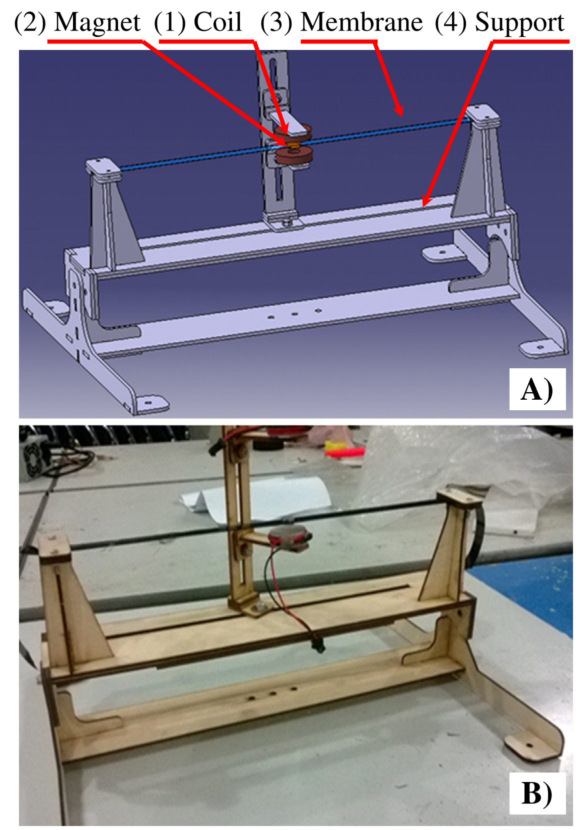

Fig. 2. (A) 3D design. (B) Fabricated test model.

To study effects of different parameters, the test model must satisfy the following requirements:

- operating well in the wind tunnel (Table 2);
- pre-applied tension force, direction, magnet position, membrane's angle of attack can be easily modified.

Experiment setup to study the effects of design parameters on operational characteristics of the windbelt

Fig. 3 shows the experiment setup and also experiment procedure.

The test model is put in the wind tunnel where the air flow velocity (wind speed) can be changed precisely from 0 m/s to about 30 m/s. Air flows through the tunnel as it operates to generate induction power. The output signals (voltage and current) then go through an analog/digital converter which is connected to a computer. Thus, the output voltage and current data will be directly registered, stored, and processed.

Table 1
Characteristics of the test model.

Parameters	Value	Unit
Pre-applied tension	0–50	N
Angle of attack	$0 - \pm\frac{\pi}{3}$	rad
Dimension	$0.35 \times 0.2 \times 0.2$	m
Dimension of membrane	0.01×0.35	m