Design of Aeroelastic Wind Belt for Low-Energy Wind Harvesting

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Abstract. Malaysia plans to increase the total renewable energy mix to 30% by the year 2030 as part of the Green Technology Master Plan. Currently, the role of wind power is not included in the renewable energy mix of Malaysia and diversification of the renewable energy mix needs to be encouraged to include policy support for other sources of energy. The wind speed Malaysia is ranged from 3-7 m/s and most wind turbine requires 5 m/s as cut in speed. The low average wind speeds causes wind turbine to be the least cost-effective method to generate electricity at Malaysia especially at the west coast. Therefore, low-energy wind harvesting device is proposed as alternative at this climate. This device is also intended to generate power from vehicle-induced wind. Three potential configurations (electromagnetic, piezoelectric or electrostatic) for small-scale energy harvesting device were proposed by previous researchers and studied in this work. Electromagnetic configuration of energy harvesting by fluttering was selected after analysis of three configurations. A wind belt was designed to withstand environmental conditions such as fresh water (rain), UV radiation and acid/alkali conditions. Several important parameters such as belt width, location of the magnet etc for the design were evaluated experimentally. Taffeta silk was selected as the belt materials from potential materials. The optimum length and width of the belt in this study are 1 m and 12 mm. Neodymium N45 magnet was selected based on inductance and the optimum magnet position along the belt is 20cm from the edges of the main frame. Experimental results showed the peak power recorded in parallel connection are 81.02 mW @ 6 m/s with a belt tension of 0.816 N and 24.54 mW @ 4 m/s with belt tension of 0.612 N.

1. Introduction
In Malaysia, the wind speed is ranged from 3 -7 m/s depends on the location while the monthly mean wind speed values are between 1.5 m/s to 4.5 m/s [1]. Most of the commercial available horizontal axis wind turbines are not cost effective in Malaysia. This is because the capacity factor would be extremely low at approximately <20% due to its inability to achieve the cut-in wind speed. Hence, an alternative device to capture wind energy at low wind speeds would be deemed suitable for this climate. Wind belt or wind fluttering energy harvester was proposed by Frayne in 2004 [2] and was investigated by various researchers [3-4].

The three widely used mechanisms for small-scale wind fluttering energy harvester are the electromagnetic, piezoelectric and electrostatic methods. All three mechanism shared a common working principle which is to convert vibrations to a usable electrical output (current). The strengths
and weakness of the piezoelectric, electromagnetic and electrostatic mechanism were compared based on seven factors and then electromagnetics method was selected for further design [5]. Wind belt capitalises on generated vibrations from the fluttering belt based on an effect called “Aeroelastic Flutter”. The Aeroelastic flutter makes use of the wind energy by capturing the kinetic energy of wind and it is a self-feeding vibration of an elastic structure when faced with air flow [3]. This relative movement causes a change in the magnetic field which is also known as a magnetic flux, thereby generating electricity in the form of current. Wind belts were designed and studied by several researchers. Arroya et al. designed an omnidirectional wind energy harvester which can harvest low speed wind from all directions [3] whereas Aquino et al. proposed to power wireless sensors and other small scale electronics devices of building by wind belt [4]. Pimentel et al. studied parameters such as belt tension, and angle of attack that affect the Humdinger’s wind belt in a wind tunnels. The optimum tensions are 8.1 N @ 3.6 m/s and 36 N @ 7 m/s whereas the optimum cut-in angle of attack is 40 degree at 3.6 m/s and 4 m/s to 55 degree at 10 m/s [6]. Laštovička-Medin confirmed belt’s stiffness and length of the belt are important factors to affect the performance but no further analysis was done [7].

Several parameters such as materials, dimension and tension of the wind belt, might affect the performance the wind belt. However, this information is not available in the established database. As such, this work aims to study the influence of the position of magnet, dimension and tension of the belt on the output power.

2. Methodology

A wind belt prototype was first designed using CREO Parametric 4.0. The wind belt energy harvester consists of three mechanisms; a mechanism to convert wind energy to kinetic energy, a mechanism to convert kinetic energy to electricity, based on Faraday’s law of induction, and a power conditioning mechanism. The details of the power conditioning mechanism is not presented in this paper. The important design parameters are determined through literature review. Next, four parameters which are the magnet position, belt width, wind speed and belt tension are investigated through lab testing in this work.

![Figure 1. CAD of Electromagnetic Wind Belt](image-url)

A CAD of the electromagnetic wind belt is shown in Figure 1. A belt (a) is fixed by L-bracket fasteners (b) at one side and connected to adjustable tensioner bracket on the other side. The tension of the belt can be adjusted by a screw on the tensioner bracket (c). Two magnets (d) are attached on the top and bottom surfaces of the belt, and in total four magnets are used. Four copper coils (e) are placed on the main frame, facing the magnet. The material of the main frame (f) is PVC cross-linked foam. The incoming wind will induce longitudinal and torsional displacement in the wind belt with high frequency oscillatory motion. Therefore the dimension and material of the belt are important factors that affect the performance of wind belt energy harvester. Previous works showed for wind speeds higher than 10 m/s, the wind belt length should be in a range shorter than 50 cm. However, for wind speeds between 5-10 m/s, the ideal wind belt length would be between 50 cm to 100 cm to ensure that the fluttering effect is existent [8]. In order to cater Malaysia’s climate, the length of the wind belt is fixed at 1 metre. The belt’s width is a parameter to be determined in this work. It is vital that the wind belt to be light-weight so that the cut-in speed will be minimized as well as high torsional resistance to
ensure linear oscillation. Three different materials, taffeta, and two different grades of Mylar are acquired for testing.

Two button magnets were attached to the ribbon in-line with the centre of the copper coils. As the magnets flutter either in longitudinal/torsional orientation along with the wind belt, the polarity of the field through the copper coil changes which results in an alternating current. The main criteria for the choice of the magnet is the remanent inductance (Br), which is quantified by Tesla. The magnitude required is between of a range of 1.3 T to 1.4 T according to Ramasur, D. et al. [9]. The material chosen for the magnet is Neodymium, particularly the N52. The dimensions of the magnets are 12 mm x 4 mm. The copper coils have a wire core diameter of 0.13 mm (SWG 40 grade). SWG 40 was chosen for this study because of the low resistance per metre length of wire, highest formability(ductility) for winding the highest number of turns possible (specifically 6000 turns) and resistance to fresh water (rain), salt water and UV radiation. The selection criteria are the formability, solderability, electrical conducting strength, resistance against UV radiation, fresh and salt water. Copper was ultimately chosen for the coil because of the availability of pre-rolled coils in the Malaysian market along with its reasonable pricing.

The calculation of the belt tension will be done using Young Modulus formula as shown below.

\[
E = \frac{FL}{A\Delta L}
\]  

where, 
\( E \) = Young’s Modulus in pascals (Pa) 
\( F \) = Force in Newtons (N) 
\( L \) = Original length in metres (m) 
\( A \) = cross-section area in square metres (m²) 
\( \Delta L \) = change in length in metres (m)

The belt material is chosen as the taffeta silk which is made from silk produced by a silkworm known as “Bombyx Mori” [10] with Young Modulus of 8.5GPa [11]. The belt’s tension at different elongation and three different width were measured, calculated, and presented at Table 1. The value calculated is synonymous with a study done by Arroyo.E et al [3], where the studied tension varies from 0.1 N to 3.0 N.

| Belt Width | 2 mm  | 4 mm  | 6 mm  | 8 mm  | 10 mm | 12 mm |
|------------|-------|-------|-------|-------|-------|-------|
| 12 mm      | 0.204 N | 0.408 N | 0.612 N | 0.816 N | 1.02 N | 1.224 N |
| 18 mm      | 0.306 N | 0.612 N | 0.918 N | 1.224 N | 1.53 N | 1.836 N |
| 24 mm      | 0.408 N | 0.816 N | 1.224 N | 1.632 N | 2.04 N | 2.448 N |

Three design parameters which are the magnet position, belt width, and belt tension are investigated in this work. The parameters are tested by two sets of coils, one set at the top of the frame “top set” and one set at the bottom of the frame “bottom set”. Figure 2 shows the set-up during the bottom coil testing phase. The tension of belt can be altered by the screw. The copper coils were connected in series with crocodile clips attached to one end of each coil whereby the output will be shown on an oscilloscope. An anemometer was placed behind the ribbon to measure the wind speed induced by an industrial leaf blower. Magnet positions on the wind belt were tested first at a range of 5 cm to 30 cm from the left and right side of the frame with step increments of 5 cm to determine the optimum position for peak output generation. Experiments were conducted with three different belt width 12 mm, 18 mm and 24 mm to examine the behaviour and geometry of the belt. The wind speed tests will range from 2 m/s to 12 m/s with increments of 2 m/s whilst the tension from 0.204 N to 1.224 N with six step increments and was plotted in a power matrix table. For all the experiments, the measurements were averaged over 5 data points.
3. Results and Discussion

In Figure 3, the test was carried out with constant parameters of belt tension at 0.816 N and wind speed of 6 m/s, it is evident that the best performance stems from the 12 mm belt width, a negative linear relationship is observed with step increment of the belt width, it is apparent that the wind belt starts to sag at belt widths higher than 12 mm due to the weight of the magnet, possibly disrupting the fluttering phenomenon. In figure 4, the optimum magnet position from the edges were 20 cm, however with further increment of the magnet position the 20 cm step, the output power seems to decrease exponentially to 5 mW at 30 cm. Overall, and the bottom set of copper coils has the highest average generation of power.

Table 2. Voltage generation from wind speed/belt tension manipulation

| Voltage Speed (m/s) | 0.204 | 0.408 | 0.612 | 0.816 | 1.020 | 1.224 | 0.204 | 0.408 | 0.612 | 0.816 | 1.020 | 1.224 |
|---------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| Belt Tension(N), bottom set | 3.0 | 2.5 | 1.4 | 0.3 | 0.0 | 0.0 | 2.7 | 1.9 | 0.9 | - | - | - |
| Belt Tension(N), top set | 3.6 | 4.0 | 5.2 | 4.6 | 2.6 | 0.0 | 3.3 | 3.9 | 4.6 | 3.2 | 1.4 | - |
| 6 | 3.0 | 5.6 | 6.7 | 8.6 | 6.1 | 4.8 | ! | 5.2 | 7.4 | 8.2 | 6.1 | 3.7 |
| 8 | 0.0 | 5.1 | 8.5 | 11.2 | 13.3 | 9.2 | ! | 4.9 | 8.2 | 10.4 | 12.3 | 8.5 |
| 10 | 0.0 | 0.0 | 9.6 | 14.0 | 17.6 | 15.4 | ! | ! | 9.1 | 13.4 | 15.8 | 12.5 |
| 12 | 0.0 | 0.0 | 8.4 | 12.8 | 19.2 | 21.0 | ! | ! | 7.9 | 10.4 | 16.7 | 20.6 |

* “-” denotes negligible voltage generation due to high elastic potential energy across the belt
* “!” denotes high belt eccentricity resulting in invalid readings
The relationship between the wind speed/belt tension and RMS open-circuit generated voltage (V) for the top set and the bottom set is presented in Table 2. The resistance and inductance for the top sets and bottom sets of the coils are 713 Ω; 5.2 H and 857 Ω; 6.1 H. The results were recorded to determine the critical flutter speed and cut-out speed of the belt under various wind speed and belt tension combinations. Each wind speed magnitude has the most suitable belt tension configuration associated with it; the 12 m/s wind speed and 1.224 N belt tension combination which has a peak open-circuit voltage of 21.00 V. However, the voltage begins to decrease after the peak configuration due to the cut-out tension approaching which is explained in next section. The trends observed as shown below:

- 0.612 N belt tension appears to accommodate 2-12 m/s of wind speed [Largest Range]
- Multiplication of roughly x2.4 times when wind speed tested from 8 m/s to 12 m/s wind speed @ 1.224 N belt tension, from 8.50 V to 20.6 V for the top set in Table 2.
- 2 – 4 m/s wind speeds have higher compatibility with lower grade tensions due to less elastic potential energy
- Bottom set has highest overall voltage generation

The analysed results are synonymous with a study done by Pimentel et al. [6]. The belt tension varies with difference in wind speed because external kinetic energy needs to exceed the elastic potential energy in the belt.

| Power (mW) | Belt tension (N) |
|-----------|-----------------|
| Wind Speed (m/s) | 0.204 | 0.408 | 0.612 | 0.816 | 1.02 | 1.224 |
| 2         | 18.6          | 15.3          | 6.5           | -           | -           | -           |
| 4         | 19.8          | 20.5          | 24.5          | 18.9        | 6.4          | -           |
| 6         | -             | 44.1          | 64.7          | 81.0        | 44.7         | 28.1        |
| 8         | -             | 41.7          | 78.6          | 102.6       | 124.6        | 81.7        |
| 10        | -             | -             | 94.9          | 188.7       | 224.9        | 188.1       |
| 12        | -             | -             | 76.2          | 124.0       | 311.8        | 346.1       |

Table 3. Power matrix table for power generated from prototype

For optimization of wind speeds in Malaysia, it is recommended to use a belt width of 12 mm and a belt tension of 0.612 N for maximum power generation. The wind belt can be installed on the divider of highway to generate electricity for street lights/signage. Table 3 is a power matrix table of ranging wind speed from 2 m/s to 12 m/s along with belt tension, the main product of this table is the power generated in mW with the top and bottom sets of the copper coils connected in parallel. The rated power generated is 346.08 mW @ 12 m/s wind speed; 1.224 N belt tension. Since the annual average wind speed of Malaysia is 3-9 m/s, the closest median wind speed is assumed will be 6 m/s, optimized with a belt tension of 0.816 N. Hence, power generation of 81.02 mW will be assumed for the annual power production calculation.

| Authors               | Wind Speed (m/s) |
|-----------------------|------------------|
| Current study         | 11.35 mW         |
| Kanhe et al. (2017)[12]| 18.45 mW         |
| Laštovička-Medin (2018)[7] | 41.20 mW         |
| Pimentel et al.(2010)[6] | 25.70 mW         |

Table 4. Study comparison between other researchers
The performance of current work is benchmarked with previous works and tabled in Table 4. The output power from 4 m/s to 6 m/s shown in the current study with one set of copper coil connected in series are slightly lower compared to 4 m/s of Laštovička-Medin [12] and 6 m/s of Pimental et al. [10]. However, at a wind speed range of 8 m/s to 12 m/s, the performance in output power shows a positive and encouraging trend for the current study.

4. Conclusion and future works
The electromagnetic based wind belt for Malaysia’s climate was designed based on literature review and parametric studies of selected parameters. To capture Malaysia’s wind speed, the length and width of the taffeta silk belt are proposed to be 1 m length and 12 mm width. The optimum magnet position along the belt is 20 cm from the edges. These optimized parameters were then used as the constant parameters for the wind speed/belt tension combination experiment. The peak output voltage and power recorded whilst the four coils are connected in parallel are about 21.00 mW @ 12 m/s wind speed; 1.224 N belt tension. The peak power recorded in parallel connection at lower wind speed are 81.02 mW @ 6 m/s with a belt tension of 0.816 N and 24.54 mW @ 4 m/s with belt tension of 0.612 N. Future works include:
- The wind belt can be tuned to optimize the output at different wind speeds provided that further in-depth research is done for the coil winding methods to optimize for lower resistance for higher current output [13].
- Optimizing better coil set-up and arrangement towards denser packing so that the resistance can be reduced and higher permeability within the area of effect of the neodymium magnet, for higher current output.

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