中國機械工程學刊第四十一卷第三期第 345~351 頁(民國一百零九年)
Journal of the Chinese Society of Mechanical Engineers, Vol.41, No.3, pp 345~351 (2020)

Quantification of Aeroelastic Wind Belt for Malaysia*

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Keywords: Wind belt, Low speed wind harvester, Wind energy

ABSTRACT

The wind speed Malaysia is ranged from 3-7 m/s and most wind turbine requires 5 m/s as cut in speed. Hence, 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 and 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 20 cm 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. The acquired results can be acted as a guide for design of wind belt.

INTRODUCTION

The composition of the renewable energy mix in Malaysia mainly consists of solar PV, followed by biomass, small hydro and biogas (Figure 1) in which the policy support in terms of feed-in tariffs are readily available.

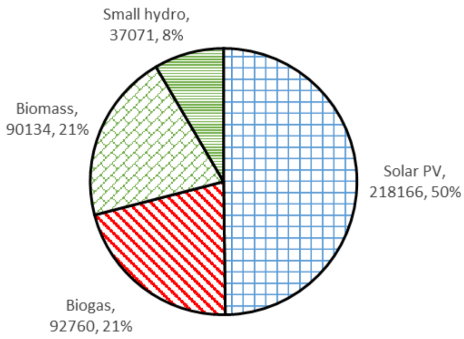

Fig. 1: Current renewable energy mix of Malaysia, in MWh, reproduced from (SEDA.gov.my, 2017)

However, to increase the total renewable energy mix to 30% by the year 2030 as part of the Green Technology Master Plan (GTMP) for the energy sector by 2030 (St.gov.my, 2018), diversification of the renewable energy mix needs to be encouraged to include the policy support for other sources of energy such as wind and wave power, which is potentially feasible in Malaysia. 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 (Mohammad Rafiqul 2011). 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. In addition, horizontal axis wind turbines are still having numerous problems to be resolved. One example is the interference between rotor blade and the tower of the wind turbine that affect the drag characteristics, studied by Haroon Rashid et al. 2018. They showed that for tower with rotating rotor, the drag coefficient is increased with the Reynolds number. 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 (Briand et al. 2015) and was investigated by various researchers (Arroyo et al. 2014, Pimentel et al.

Paper Received March, 2019. Revised September, 2019, Accepted September, 2019, Author for Correspondence:Tze Chuen Yap

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2016, Atrah et. al, 2017, Aquino et al. 2017, Fernandez et al., 2018 etc.).

The main concept of wind fluttering energy harvester is to convert vibration to a usable electrical output which is current, converting vibrational energy is a two-step process. It is converted in a relative motion between two elements with the help of a mass-spring system that acts as a storage of energy. Then the energy is funnelled into a mechanical-to-electrical converter. The three widely used converter mechanisms for small-scale wind fluttering energy harvester are the electromagnetic, piezoelectric, and electrostatic methods. 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 (Vinayan 2018). 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 (Arroyo et al. 2014). 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. Arroya et al. designed an omnidirectional wind energy harvester which can harvest low speed wind from all directions (Arroyo et al. 2014) whereas Aquino et al. proposed to power wireless sensors and other small scale electronics devices of building by wind belt (Aquino et al. 2017). 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 (Pimentel et al. 2016). The belt's stiffness was investigated by Chen et al. 2016. They developed a theoretical frame work for flutter of both 'stiff' and 'flexible' materials. They also concluded that the flutter frequency of still material is independent of wind velocity whereas flutter frequency of flexible material is proportional to wind speed (Chen et al. 2016). Laštovička-Medin confirmed belt's stiffness and length of the belt are important factors that affect the performance but no further analysis was done (Laštovička-Medin 2018). Fernandez et al. optimised the piezoelectric wind belt design parameters such as the belt length, belt material, frame length and also the exposed length of piezoelectric transducer. From their experiments, the optimum belt is 0.75 m latex rubber, optimum frame length is 0.86 m, and optimum exposure of the piezoelectric transducer is 75% for a wind speed about 3 m/s (Fernandez et al., 2018). Ahmad and Khan (2018) focused on the vibration aspect of vibration energy harvester. They studied multiple modes and nonlinear behaviour in electromagnetic energy harvester. They developed an electromagnetic type vibration energy harvester and detected three natural frequencies existed in the device. The device can be tuned to desired modes by altering the design and the mass of the magnet (Ahmad and Khan, 2018). This concept can be applied on wind belt to optimise the performance. On the other hand, some researchers proposed to improve the performance of the wind belt by adding a cylinder in front of the wind belt to create Karmen Vortex entering the wind belt (Atrah et. al, 2017).

Several design parameters such as materials, dimension and tension of the wind belt, might affect the performance the wind belt. However, their relationship is not widely studied, especially for electromagnetic wind belt. In addition, there is a noticeable lack of studies relating to optimal design of small-scale energy harvesting for Malaysia's environment.

As such, this work aims to study the influence of the position of magnet, dimension and tension of the belt on the output power of an electromagnetic wind belt. In addition, this work also review and compare related policies.

METHODOLOGY

A wind belt prototype was first designed using CAD software (CREO Parametric 4.0). The wind belt energy harvester consists of three mechanisms; i) a mechanism to convert wind energy to kinetic energy, ii) a mechanism to convert kinetic energy to electricity, based on Faraday's law of induction, and iii) 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.

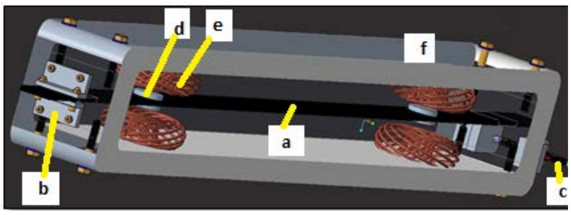

Fig 2. CAD of Electromagnetic Wind Belt

A CAD of the electromagnetic wind belt is shown in Figure 2. 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 main frame was constructed with four pieces of material which are the top and bottom panels and two side panels, joined together by M8.0 stainless steel hex screws. Since the most important aspect of this component is the lifespan and resistance to the external environmental conditions (Ramasur and Hancke 2012), PVC cross-linked foam (closed cell, DH 0.130) was selected. 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 (Jagan and Bose 2015). 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. The Poisson's ratio of the belt material should be around 1.00 so that the belt will not change shape longitudinally when tension is exerted. Beside this, the belt material should have a Young's Modulus of around 10 GPa so that plastic deformation will not be exceeded during the testing phase. Three different materials, taffeta, and two different grades of Mylar were acquired for testing and only the taffeta's results were presented here.

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 (Ramasur and Hancke 2012). The material chosen for the magnet is Neodymium, particularly the N52, and the dimensions of the magnets are 12 mm x 4 mm. The coils were selected based on formability, solderability, electrical conducting strength, resistance against UV radiation, fresh and salt water. Copper coils with wire core diameter of 0.13 mm (SWG 40 grade) were chosen because of the low resistance per metre length of wire, highest formability (ductility) for winding the highest number of turns possible (specifically 6000 turns), resistance to fresh water (rain), salt water & UV radiation and also the availability of pre-rolled coils in the Malaysian market along with its reasonable pricing.

The belt tension is calculated based on the Young Modulus formula as shown below.

$$E = \frac{FL}{A\Delta L} \tag{1}$$

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 (m^2)
ΔL= change in length in metres (m)

Table 1. Belt width, strain and estimated tension in the wind belt

	Change in Length (Strain)					
Belt Width (mm)	2 mm	4 mm	6 mm	8 mm	10 mm	12 mm
12	0.204 N	0.408 N	0.612 N	0.816 N	1.02 N	1.224 N
18	0.306 N	0.612 N	0.918 N	1.224 N	1.53 N	1.836 N
24	0.408 N	0.816 N	1.224 N	1.632 N	2.04 N	2.448 N

The belt material is chosen as the taffeta silk which is made from silk produced by a silkworm known as "*Bombyx Mori*" (Ude et al. 2014) with Young Modulus of 8.5 GPa (Loh and Tan 2011). 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 et al. 2014), where the studied tension varies from 0.1 N to 3.0 N.

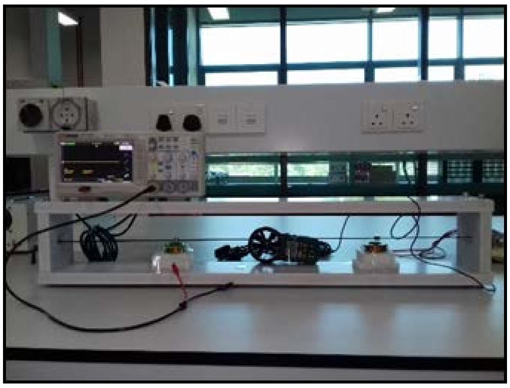

Fig. 3. Experimental set-up for testing (bottom set)

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 3 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 was ranged from 2 m/s to 12 m/s with increments of 2 m/s whilst the tension varied from 0.204 N to 1.224 N with six step increments. For all the experiments, the measurements were averaged over 5 data points. In this experiment, the tension of belt is assumed to be a constant during and after the experiment and the change in belt length is proportional to the tension force.

RESULTS AND DISCUSSION

In Figure 4, 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. The dimension of the neodymium magnets used in this study are Ø 12 mm x 4 mm. No sagging was apparent for the 12 mm belt width because the magnet circumference compliments the belt width resulting in even distribution of weight on the 12 mm belt, therefore the profile can be assumed as a 2D flat plate for this case. As for the 18 mm and 24 mm belt width, minimal amount of sagging was observed due the mass of magnet concentrated at the belt centre. The sagging is represented by the red region in Figure 5. The profile of the wind belt directly influences the power generation, because profiles with “hill” shapes shown at 18 cm and 24 cm hinders the fluttering amplitude and frequency due to an additional vortex present behind “hill” profiles.

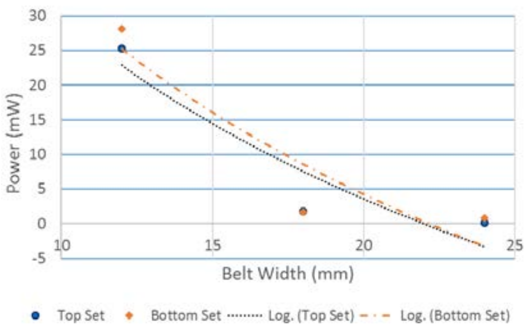

Fig. 4. Power (mW) vs Belt width (mm)

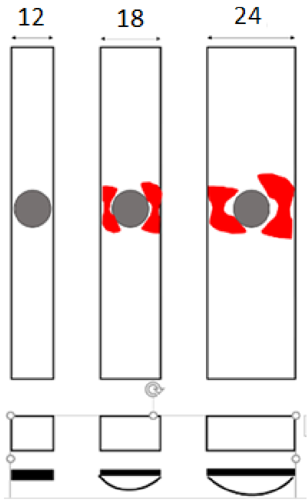

Fig. 5: Belt Width (mm) Top View

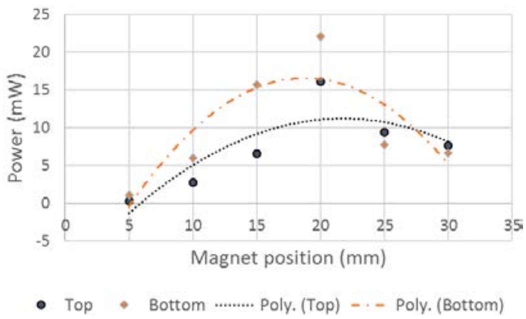

Fig. 6. Power (mW) vs Magnet position (cm)

In Figure 6, 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. Generally, the bottom set of copper coils has the highest average generation of power. 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. 2010. The belt tension variates with difference in wind speed because external kinetic energy needs to exceed the elastic potential energy in the belt.

The belt is assumed to be a linear elastic spring model with one degree of freedom at the one end of the ribbon which undergoes tension/compression in the length-direction as testing will not include exceeding the plastic deformation limit of the belt material, hence a first-order linear approximation of Hooke's Law can be applied here. In this case, the same force/tension is expected to be applied along the cross section of the ribbon**.** Based on the results shown in Table 3, particularly at 2 m/s and with 1.020 N and 1.224 N, the voltage generated is negligible because of failed vibration excitation.

Hence, there is a certain activation energy needed to excite the fluttering mode at the aforementioned tension values. Elastic potential energy (deformation energy) is stored in the taffeta ribbon when tension is exerted upon it uniformly. In order to exceed the elastic potential energy for the fluttering phenomenon to be activated, the external kinetic energy (wind vortexes) needs to be higher than the stored potential energy in the belt. Any generation system will at any point achieve dynamic stability/equilibrium, whether in the form of vibration (fluttering effect) or rotation with the external loads, which in this case will be the incoming wind.

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.

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

Voltage	Belt Tension(N), bottom set						Belt Tension(N), top set					
Wind 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
2	3.0	2.5	1.4	0.3	0.0	0.0	2.7	1.9	0.9	-	-	-
4	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

Table 3. Power matrix table for power generated from prototype

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 4. Study comparison between other researchers

Authors	Wind Speed (m/s)					
	2	4	6	8	10	12
Current study	11.35 mW	27.25 mW	56.79 mW	84.61 mW	127.36 mW	173.52 mW
Kanhe et al. 2017	-	18.45 mW	-	-	-	-
Laštovička-Medin 2018	-	41.20 mW	-	-	-	-
Pimentel et al. 2010	-	25.70 mW	68.00 mW	78.00 mW	102.85 mW	-

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, 2018) and 6 m/s of (Pimental et al., 2010). However, at a wind speed range of 8 m/s to 12 m/s, current study managed to obtain higher output power.

Currently feed-in tariffs at Malaysia are only available for Solar PV, Biogas, Biomass and Small Hydro, which will not be applicable for aeroelastic wind belt if it were to be adopted at a larger scale. In additional, the net energy metering policy in Malaysia only widely supports Solar PV technology of under 500 MW (SEDA 2018) compared to the Bipartisan Budget Act of 2018 in the US, which reinstates tax credit for fuel cells, micro-scale wind energy harvesting devices and geothermal heat pumps. In the US, a variety of technologies is included in the net metering policies. All states have solar energy in their net metering policies, and they may include: wind and micro-turbines, fuel cells, small hydroelectric, tidal energy, wave energy, biomass, biogas, landfill gas, municipal solid waste, anaerobic digesters, geothermal electric, combined heat and power or cogeneration, ocean thermal and renewable fuel cells (Ncsl.org., 2017). Hence, similar policy is required to promote the adoption of wind belt technology in Malaysia. Wind belts are widely proposed to power low power sensors. Wind belts can also be used to tap the vehicle induced turbulence on highway to power highway lighting.

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. The optimum belt tension variates with difference in wind speed because external kinetic energy needs to exceed the elastic potential energy in the belt. 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 V, generating 346.08 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 (Singh, 2017).
- 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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