PRELIMINARY TESTING OF A NEW VIBRATION ENERGY HARVESTER

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ABSTRACT

A novel technology designed to use flow induced flutter in a tensioned strap as the driving force for electric energy generation is preliminarily studied. Our device harnesses wind energy by using a tuned surface vibrating in airflow. As an unstable surface, under tension, encounters airflow it vibrates causing the distance spanned by the surface to oscillate. We tune the tension on the surface to achieve a large amplitude flutter over a short period. This motion drives a ratchet and flywheel arrangement which can turn a generator. Prototype systems have shown promise including the flywheel output in excess of 750 RPM. This paper only reports on the preliminary design of the system along with methods for increasing pseudo-instability and the performance of the ratchet and flywheel assembly.

NOMENCLATURE

AoA – Angle of Attack
α – Angle of Attack
ρ – Air Density
c – Chord Length
C_L – Coefficient of Lift
ℓ – Length of Strap
Δℓ – Effective Change in Length of Strap
L – Lift
U – Velocity of Flow
V – Velocity of strap
W – Weight of Strap
ΔW – Weight Added to Strap
T – Overall Strap Tension
T_L – Leading Edge (Upstream) Tension
T_T – Trailing Edge (Downstream) Tension

1. INTRODUCTION

Wind energy is a widely available, affordable, reliable, and rapidly deployable electric generation method [1]. In 2017, the American Wind Energy Association reported that U.S wind energy alone provides enough electricity to power the equivalent of over 25 million homes with an installed capacity of 8,203MW[2][3]. In the eastern hemisphere, the International Energy Agency reported that by 2030, 600 million out of the 674 million people without access to electricity will live in sub-Saharan Africa, a majority of them in rural areas [4]. This is where the demand for a renewable off-grid power generation system is high. The vibration energy harvester concept introduced in this paper is a patent pending device that harnesses the vibrations of a tensioned surface exposed to an airflow. The unstable vibration of tensioned rigging was observed during sailing and the idea of a stand-alone system to extract energy from a tensioned surface with fluid interactions was conceived. The development of these devices has involved designing a system to achieve constructive interference and large amplitude semi-stable oscillation which is not normally a feature desired in a bluff body design.

This paper presents the results of the preliminary studies conducted on the proposed device. The focus is on the design of the system along with methods for increasing pseudo-instability both through tension tuning, surface mounting, and strap geometry as well as the performance of the ratchet and flywheel assembly. Section 2 discusses the underlying operating principles of the proposed system. An overview of the physical model and the experimental setup is provided in Section 3. Section 4 introduces the methods for optimizing the performance by variable tensioning and strap geometry. A preliminary mathematical model is presented from the results in Section 4.
2. BACKGROUND

The proposed system relies upon an elastically retracted flutter mode in the main strap causing deflection and shortening of the effective span of a soft or semi-rigid structure, referred to as the strap. The strap oscillates in a flutter mode similar to the first harmonic due to the force of the flow around the strap and the variable tension in the leading and trailing ends. For a given force normal to the strap the possible angular deflection in the strap is a function of the tension. By tensioning the upstream edge of the strap slightly more than the downstream edge it is possible to ensure that the downstream edge oscillates with a larger amplitude than the upstream edge. This causes the oscillation shown in Fig1.

When the strap is at equilibrium (Fig1: A) it has an angle of attack (AoA) of zero and is unstable in a flow as demonstrated by Baik et al. [5]. Over a short timespan, this instability will cause the leading edge of the strap to deflect causing an increase in the angle of attack in a manner analogous to that observed in ridged wing flutter generators [6]. The strap, now having a non-zero AoA then deflects the flow around it (Fig1: B) creating lift and an increase in drag. This lift begins to force the strap in the direction of lift which is mostly normal to both the direction of the flow and the direction of the strap. This motion indicates the beginning of the power stroke as the strap begins to move $v(t_0)$ in Fig. 1. Due to the endpoints of the strap being fixed this movement is experienced differentially along the length of strap and a deflection occurs along its length. This deflection is opposed by the tension in the strap as the tensioning system elastically attempts to return the strap to equilibrium in order to minimize elastic strain in the strap.

As the strap deflects along its length the tension increases and the rate of deflection slows in proportion to the lift and tension forces encountered. The leading edge of the strap deflects at a slower rate than the trailing edge due to the former is more highly tensioned. This causes the angle of attack to decrease during the stroke to the point where there is no longer enough lift present in the strap to overcome the tension attempting to return the strap to equilibrium as shown in Fig.1 C. The strap then begins to be elastically retracted and with appropriate tuning the leading edge overtakes the trailing edge (Fig1. D) in returning to equilibrium due to the higher tension in the leading edge; more quickly retracting it. This change of sign in the angle of attack is referred to as inversion of the strap and signals the end of the power stroke and the beginning of the backstroke. This then induces lift in the new direction of motion and the strap continues through equilibrium beginning a new stroke (Fig1.E & F).

For a strap with a non-zero weight per unit length, momentum of the strap becomes a factor and it is possible through an appropriate tuning of tension to achieve a driven harmonic flutter analogous to the destructive flutter avoided during the design of suspension bridges and aircraft [7]. While in most standard applications this constructive interference would be tuned out of the system, we design to purposefully re-enforce this mode. The excess energy produced by this driven flutter is harnessed by the generator and as such damping is achieved and damage to the system is avoided.

During experimentation power from the driven deflection of the strap is extracted by a device which harnesses the change in effective span induced by the deflection of the strap. This energy is used to spin a flywheel where the number of revolutions per second (RPM) is measured.

![Diagram](image)

**FIGURE 1:** THE STRAP UNDERGOING A HALF CYCLE. THE LEFT SIDE IS SPANWISE VIEW UPSTREAM WHILE THE RIGHT IS THE CHORDWISE VIEW.

3. EXPERIMENTAL APPARATUS

3.1 Experimental Setup

A schematic of the proposed system is shown in Fig. 2. In the set-up, the strap labeled 1 is constructed from layers of thin plastic film with a weight of $47.2\pm0.1$ g/m². The straps have linear mass densities and chord lengths as shown below. The overall length of the strap, referred to as length hereafter can be varied for each of the below straps to lengths of 0.7 m, 1 m and 1.5 m all with an accuracy of +0.005 m.

**TABLE 1: PROPERTIES OF STRAPS**

<table>
<thead>
<tr>
<th>Strap</th>
<th>Chord Length (mm)</th>
<th>Linear mass (g/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>38+/−5</td>
<td>7.44+/−0.07</td>
</tr>
<tr>
<td>2</td>
<td>64+/−5</td>
<td>13.0+/−0.1</td>
</tr>
<tr>
<td>3</td>
<td>127+/−5</td>
<td>16.5+/−0.2</td>
</tr>
</tbody>
</table>

The active end of the strap is attached to the generator gearbox at the input end of the power extractor (labeled 2) by means of a wire running through a linearization plate to constraint the motion. The linearization plate (not shown) allows the linear motion of the wire to drive a ratcheting mechanism which produces rotational motion to drive the generator gearbox. Two parallel tensioning systems labeled 3 and 4 are located at the active end are positioned at the leading and trailing edge of the strap, respectively, to accommodate a variable strap stiffness. Moreover, the leading-edge tensioning system also retracts the
ratcheting mechanism. The dead end of the strap is fixed to a vertical upright allowing the strap to remain in line with the mean wind flow direction. This apparatus is then placed a specified distance in front of a high-volume fan capable of sustaining flow speeds of 6.6+/−0.4m/s at the leading edge of the strap, and allowed to reach equilibrium. Once this has occurred the behavior of the flywheel is filmed using a high speed (8X slowed) video camera. In specified tests, the behavior of the strap is also filmed for qualitative analysis.

![Diagram of the proposed system](image)

**FIGURE 2:** A BLOCK DIAGRAM OF THE PROPOSED SYSTEM. COMPONENTS ARE LABELED: 1-STRAP, 2-POWER EXTRACTION SYSTEM, 3-UPWIND TENSION SPRING, 4- DOWNWIND TENSION SPRING.

### 3.2 Experimental Procedure

In this preliminary study, a number of tuning variables were examined experimentally including the weight added to the strap at the active (power harvesting) end, the leading-edge tension, the trailing edge tension, the cord length of the vibrating surface, and the length of the vibrating surface.

To accommodate the addition (or attachment) of different weights at the active end of the strap, the first tuning variable is varied via the use of a custom-made mass holding apparatus. This apparatus is attached to the cord of the strap. To tension, the leading and trailing edges of the surface, the second and third tuning variables are adjusted via a tensioning system consisting of linear springs of known stiffness. The fourth and fifth tuning variables accommodate for different surface aspect ratios.

The following testing regime was followed to find the optimal state of the tuning variables:

1) The leading and trailing edge tensioning systems at the active end of the strap each had four settings. All possible combinations of upwind and downwind settings were tested for a given weight at the active end.
   a. Each experiment above was conducted at four different weight settings
   b. The strap geometry remained constant
   c. Wind source was at 1m from the strap
   d. RPM of the flywheel was recorded using high-speed camera

2) At the ideal tension and weight setting found from experiment #1, the length of the strap was adjusted to three lengths.
   a. Each experiment was conducted at a fixed strap cord length
   b. RPM of the flywheel was recorded
   c. Wind source was at 2 m from the strap

3) At the ideal tension and weight setting found from experiment #1, the strap cord length was adjusted to three lengths.
   a. Each experiment above was conducted at a fixed strap length
   b. RPM of the flywheel was recorded
   c. Wind source was at 2 m from the strap

### 4. RESULTS

In this section, the results of three test regimes focusing on five different dimensions of the optimization state-space are reported. The first regime surveys the tensioning of the leading and trailing edges of the strap and the effect of weighting the active end. The second regime focuses on the effect of length of the strap on output RPM at semi-optimized tension settings. The final regime concerns the effect of chord length on the performance and stability of the strap.

#### 4.1 Effects of Weight and Tension on Output RPM

The goal of this regime is to establish a range of tensions for the strap to optimize oscillation that can absorb as much flow energy as possible and translate the flow into effective span changes. It is expected that the optimal overall tension of the strap is tied closely to the length, however, the mechanics of the driving force are less well understood, and it is an ongoing area of research on how to best model the aerodynamic forcing of a span undergoing high amplitude flutter [8][9]. The tests performed experimentally determined domains of optimized tension differentials for a given strap. The strap under consideration has a 0.75m span length, an 89mm chord length, weights 15g/m and is attached to the mass holding apparatus as described above.

When properly tuned it is observed that the strap undergoes a relatively small oscillation in the angle of attack about a mean of 0. Due to the short period of this oscillation, the rate of oscillation in the deflection is driven to be similarly high. It is found that the peak performance of the strap occurs when the trailing edge is set to a minimum tension in a range of 1.40-3 N less than the leading edge as shown in Fig. 3.

Figure 3 also displays the high sensitivity to downwind tension across all tensions and local sensitivity to upwind tension for low downwind tensions which is a recurring result across the state space of added weight, upwind tension, downwind tension. This is useful for informing the design of future power extraction components which may have a wider range if attached to the upwind tensioning system than the downwind system. Note that in this and the rest of the figures, the RPM is made dimensionless using the speed of the freestream flow (|U|) and the length of
strap (ℓ). Additionally, the downward tension is made dimensionless using the overall strap tension.

**FIGURE 3: AVERAGE RPM VS DOWNWIND TENSION AT A VARIETY OF UPWIND TENSIONS.**

This result is nearly uniform across the inspected range of added weights, as shown in Fig. 4. This suggests that the optimal tension differential is not highly sensitive to the weight of the active end attachment apparatus. Here, and in the rest of the paper, the additional weight is made dimensionless using the strap weight.

**FIGURE 4: OPTIMAL UPWIND AND DOWNWIND TENSIONS VS WEIGHT ADDED TO THE ACTIVE END.**

While the optimal tension differential between upwind and downwind tension is not sensitive to strap weight there was a notable impact on the maximum output RPM. The results displayed in Fig. 5 show that the ideal condition for the strap is to have as little active end weighting as possible. This is likely due to the weighting bar behaving as a simple driven-damped oscillator, unlike the strap which is undergoing flutter in which the driving frequency is coupled to the motion of the strap ensuring a wider range of reinforced frequencies [10]. The weighted bar is driven by the strap and damped by the power extraction apparatus. As such the bar has a very narrow range in which it will hit a harmonic frequency and likely improve the output of the apparatus. However, as we endeavor to develop a generator for real-world use it is not desirable to require such highly tuned components. Therefore, in the new apparatus under development, any attaching components will be kept to a minimal feasible weight.

**FIGURE 5: AVERAGE RPM VS ADDED WEIGHT AT TWO TENSION SETTINGS**

When the tension differential is decreased the strap becomes more prone to a stall failure mode outlined below and the power strokes are shorter and require finer tuning of the overall tension in the system. When the tension differential is increased we observed larger oscillations in both the strap AoA and deflection over a longer period. It appears from the qualitative analysis of high-speed videos of the strap that the trailing edge expends most of the obtained energy without inducing much overall lift. This is characterized by the trailing edge violently oscillating and achieving an extremely high AoA due to a lack of elastic retraction of the trailing edge. This oscillation causes the period of the strap oscillation to increase which reduces the measured output.

Two notable failure modes were observed in which the strap can achieve an effectively stable position and cease driving the power extraction apparatus. One, referred to as tension inversion, occurs when the trailing edge of the strap was more tensioned in comparison to the leading edge and the other, referred to as a blowout, occurs when the overall tension in the strap was too low.

In the case of a tension inversion, the trailing edge is too highly tensioned in comparison to the leading edge where the strap is seen to begin a power stroke and then stall at the deflected position. In this case, the leading edge of the strap is initially unstable and undergoes deflection. The increased lift on the strap drives the strap through a power stroke and the strap deflects. As the deflection increases the angle of attack is also increased due to the higher degree of deflection possible in the leading edge as compared to the trailing edge. This results to the strap stalling at
full deflection and achieving a semi-stable position in which a decrease in deflection results in lower tension and the retraction of the trailing edge faster than the retraction of the leading edge. Consequently, the AoA and deflecting force significantly increase. Meanwhile, any increase in the deflection leads to either a stall or the retraction of the strap due to the tension overcoming the aerodynamic effects.

In the case of a blowout if the overall tension is too low there is not sufficient tension in the strap to return it to equilibrium between strokes. In this case, the strap achieves its maximum deflection and then the drag component of the force acting on the strap causes the deflection to rotate from a primarily transverse direction to a downstream position. This position is not typically stable, and oscillation is still observed to occur, however, the oscillation occurs entirely at maximum deflection. It is during the blowout that the strap deflects downwind and then undergoes a rocking motion transverse to the direction of the flow. On the other hand, as the strap is now normatively at maximum deflection no retraction is possible and as such, no power can be extracted from the system. These two failure modes appear to set the limits for minimum differential tension and minimum overall tension, respectively.

4.2 Length of Strap
To observe the dynamics in this regime the strap length is varied, and the tuning is set to semi-optimized settings as suggested by the results from the prior test regimes. As is displayed in Fig. 6 it is found that an increase in length initially achieves higher output RPM before decreasing for higher strap lengths. Note that the length is made dimensionless using the differential length of the strap. The tension required to achieve flutter increases as the strap length increases. This is because the restorative force in the strap flutter mode is provided by the elasticity in the power collection system. In the driven-damped oscillation model of this system, the spring constant corresponds to the force required to deflect the strap. The force per meter span driving the strap away from equilibrium is the aerodynamic load on the strap due to the flow. Employing lifting line theory for a flat plate airfoil of finite length and invariant chord we find that this is roughly constant for a given wind speed, air density, and strap chord length [11].

The lift can be calculated as in Equation 1 where the value of $C_L$ is calculated as in Equation 2 via the lifting line theory for a thin airfoil. We assume that the strap behaves as an approximately 2-dimensional wing.

$$L = \left( \frac{1}{2} \right) \rho U^2 C_L$$  \hspace{1cm} (1)

$$C_L = 2\pi(\alpha) \ell c$$  \hspace{1cm} (2)

With the net deflecting force on the strap being a linear function of the length of the strap the tension increase required to reach equilibrium for small oscillation is a function of the length of the strap cubed. Thus, it is reasonable to expect the ideal tension to increase as the third power of the length of the strap.

![Figure 6: Average RPM vs Strap Length at 3+/0.3 N Upwind and 0.07+/0.1N Downwind Tension](image)

This additional tension also suggests that the tension differential between the equilibrium and fully deflected strap positions is a function of the straps length cubed.

It can, therefore, be theorized that the initial increase in output RPM occurs due to the additional force imparted by the strap on the flywheel during each power stroke. The springs used in the experimentation are varied in initial extension to increase tension. However, the K value of the given springs is not varied and as such a higher force imparted on the power extraction components results in a faster extension of the springs. This, in turn, spins the flywheel more quickly.

As the length of the strap further increases, the stroke length can be observed decreasing in the highspeed footage. While the strap is expected to output more power per stroke the film being used as the strap is likely to be absorbing output power elastically within its length. This is indicative of one limitation of the system which is the tensile strength of the strap material. It can be theorized that in a new apparatus under development which incorporates a higher tension rated strap this issue will be heavily mitigated.

4.3 Chord Length
The outcome of increasing the chord length is an initial increase in RPM as the larger surface area drive the power extractor more forcefully. If the chord length is further increased the output RPM decreases likely due to larger, but slower, oscillation in the strap.

It was found that the optimal chord length occurred at 64+/-5mm corresponding to an aspect ratio of 0.09. Below this length, the reduced surface area of the strap decreased action on the power extracting components of the system. Thus, the strap would oscillate, however, it would not effectively extend the tensioning springs. As such only partial power strokes were observed in the flywheel resulting in lower outputs.
In the model outlined in the physical principles section, the driving force imparted on the strap is proportional to the planform area of the strap and thus it is a linear function of the chord length of the strap. As such one would expect that the ideal chord length would be infinitely long, however, the chord is limited by a semi-stable mode similar to that observed in the cases of a blowout as described above. This occurs when the chord length becomes too long.

**FIGURE 7: AVERAGE RPM VS ASPECT RATIO AT A SET TENSION OF 3:1.**

This mode can be observed as a strong decrease in performance at high chord length in Fig.7. It appears to be caused by a folding of the strap near the middle of the span. This seems to occur as the strap undergoes a normal power stroke and achieve maximum deflection. When the point of inversion occurs, the leading edge cannot travel far enough quickly enough to overcome the lift and drag forces on the strap, so it rotates downstream achieving a semi-stable position. It is possible that this is indicative of limitations in the inherent elasticity of the strap suggesting new strap materials may need to be explored as discussed in the previous section.

5. CONCLUSIONS
This paper reported preliminary studies on an innovative concept for harvesting energy from wind using a tuned vibrating surface. The most infamous instance of a tensioned structure undergoing aeroelastic flutter is the case of the Tacoma Narrows bridge which was destroyed. Qualitative analysis of the high-speed footage of the device shows similarities to this case suggesting large scale application is possible. The vibration energy harvester was prototyped and analyzed at wind speeds of 6.6+/-.0.4 m/s using the following tuning variables: the weight of the strap at the active end, the leading-edge tension, the trailing edge tension, the chord length of the vibrating surface, and the length of the vibrating surface. A significant amount of data was collected to determine which state of each variable contributed to maximum instability, allowing for greater input at the entry of the generator gearbox. The results of the study are summarized as follows:

1. A small trailing edge tension leads to the highest RPMs while the output RPM was not highly sensitive to the leading-edge tension.
2. Any weighting of the active end of the strap is detrimental to output and that the tension in the strap is not sensitive to strap weighting. This is beneficial as it will allow for a variety of straps to be used on a single device.
3. The power output initially increased with both the span-wise and chord-wise lengths to an optimum. Beyond this, any additional increase in length decreases performance.
4. Stall modes occur in straps where the leading edge is less tensioned than the trailing or where the overall tension is too low.

In conclusion, these experiments have served as a survey of the state-space of the proposed device and will further inform the development of more advanced prototypes. Further research will focus on the development of a mathematical model similar to that used in the modeling of bridge flutter so that the energy states of the system may be predicted more accurately. Additionally, we intend to construct a more detailed testing apparatus both in a wind tunnel and in the field to obtain data on performance such as efficiency and power.

REFERENCES
