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DEVELOPMENT OF A CYCLIC PITCH TURBINE

Jubilee Prasad Rao
Rutgers University
New Brunswick, NJ, USA

F. Javier Diez
Rutgers University
New Brunswick, NJ, USA

ABSTRACT
A novel wind turbine design is proposed that increases turbine efficiency. The design consists of blades symmetrically positioned around a vertical axis. The blades experience cyclic pitch variations while rotating about the axis. The pitch variation is accomplished by an innovative mechanism that rotates the blades about a horizontal axis during rotation of the turbine. This controlled pitch variation allows the blades travelling upstream to be oriented horizontally so minimum drag is obtained. On the other hand, the blades travelling downstream are oriented vertically so maximum drag is achieved. Since the aiding downstream drag is maximum and the adverse upstream drag is minimum, this configuration allows for higher power output compared to conventional vertical axis wind turbines. Experiments on the turbine conducted in a water tunnel suggest an increase in power efficiencies.

INTRODUCTION
There has been an increased interest in wind turbines for power generation in the last decade because of factors like global warming and the pressing need to shift to greener power generation methods. Many different wind turbine designs exist today [1-5]. The major classification of wind turbines is based on the orientation of the axis of rotation of the blades with respect to the wind flow direction. Wind turbines with their axes parallel to the flow are called Horizontal axis wind turbines (HAWT) and they occupy a major share of the present day commercial wind turbines. Their blades' cross section resembles an aerofoil and produce lift and drag forces while wind blows over them. The lift forces generate torque and rotate the blades when wind velocity is sufficient.

Unlike HAWTs, Vertical Axis Wind Turbines (VAWT) have an axis of rotation perpendicular to the wind direction. Hence they are also called cross flow turbines. Popular VAWTs are Darrius and Savonius turbines. Different Darrius Turbine configurations exist [2] and in most cases they are not self-starting. They use the lift forces on their aerofoil shaped blades to generate the required Torque.

Savonius Turbines on the other hand are drag based turbines. Most of them have two buckets with an "S" shaped horizontal cross section and rotate about a vertical axis of symmetry. The shape of the turbine causes it to experience more drag in the down wind direction than that in the upwind direction and the net drag forces the turbine to rotate. They are simple to construct, have cheaper maintenance and work independent of wind direction [3]. The efficiency of these turbines drops very quickly with increase in rotational speed as it adversely alters the relative velocity between the wind and the buckets. Modifications to the Savonius turbine were made by Tabbasum and Probert [6] to minimize the upstream drag and to increase efficiency which resulted in adverse inertial effects of moving parts at higher speeds. A few other designs [4] use complex geared mechanisms to continuously change the angle of blades to increase efficiency, but the blade angle variation in a cycle is constrained by the gear train.

The focus of this paper is a novel vertical axis wind turbine, with simple geometry blades, that attempts to optimize the blade working cycle to minimize adverse drag thus increasing the power output and efficiency.

INSPIRATION
All birds that can fly use their wings to generate lift and thrust for locomotion. Lift and thrust are generated by the difference in air pressures around the wings which is a result of the aerofoil shape of the wings, the inspiration behind aeroplane wing design. In addition to the lift due to the aerofoil shape of the wings, birds can also flap them up and down to generate more lift. Bird's wings are spread out during the down-stroke and folded inwards during the up-stroke. Birds also pitch (rotate) their wings about a lateral axis right before the up-stroke and bring them back to normal at the end of the up-stroke. The spreading out during the down-stroke and the folding in and pitching during the up-stroke causes the effective wing area to change resulting in additional lift.

Another example of cyclic pitching is found in rowing. An oarsman rolls an oar to vary the oar blade's effective area from one stroke to another to maximize thrust [7]. The blade of an oar is held perpendicular to the water surface while pushing the water back (drive stroke) to maximize the water displaced. Then, the blade is pulled out of the water and held parallel to the water surface during the recovery stroke to minimize air drag. Thus the blades have maximum effective area during the drive stroke and minimum effective area during the recovery stroke.

Change in the wing's or blade's effective area produces net lift in the bird case and reduces drag as well as increases propulsive force in the rowing scenario. In both the above cases, changing the effective area of the blade or wing from one stroke to another is being used to improve the energy efficiency of the activity. The same principle can also be used to capture energy from a fluid flow. A similar principle is observed in some drag based vertical axis wind turbines like Savonius [3], as shown in Fig. 1, where the shape of the blades is such that they experience more drag while moving in the direction of the flow (drive stroke) and less drag when moving against the flow (recovery stroke). This differential drag between the two strokes causes a net force or torque in the direction of rotation of the turbine.

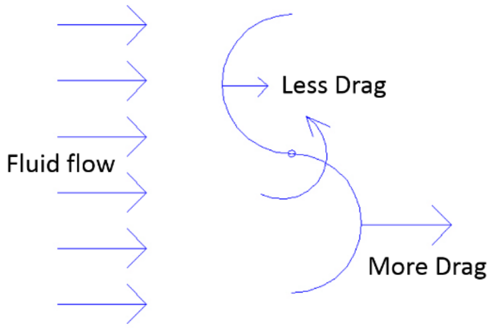

FIGURE 1. DIFFERENTIAL DRAG IN SAVONIUS TURBINE

To increase the efficiency of a device working on this principle it requires the optimization of drag forces i.e. the aiding downstream drag is to be maximized and the adverse upstream drag is to be minimized which is the focus of this paper.

CONCEPTUALIZATION

To understand and elucidate the functioning of the proposed VAWT, assume a laminar fluid flow, which is the energy source, from left to right. Introduce a solid plate of finite length l and thickness t where $l >> t$ into the flow. This is analogous to introducing a blade of an oar into water. With intuition and basic knowledge of fluid dynamics, it can be stated that the force or drag on the plate is maximum when the plate is vertical as shown in Fig. 2(a) and it is minimum when the plate is horizontal as illustrated in Fig. 2(b). If the plate is assumed to be infinitely thin, then a horizontally positioned blade would not interfere with the flow and the drag would be zero if surface effects are ignored.

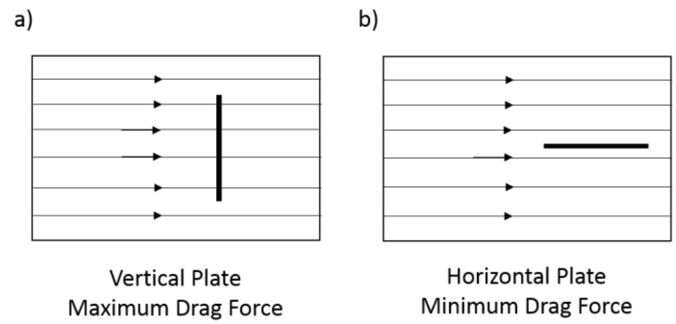

FIGURE 2. DRAG FORCES ON A FLAT PLATE

Now, imagine a zero friction mechanism that allows the plate to move left and right between two extreme points separated by a distance d such that the plate stays vertical while moving to the right and remains horizontal while travelling to the left. It can be observed that if the plate is positioned vertically at the left end, the flow would drag it with maximum force F_{max} to the right extreme point. The amount of work W_1 done on the plate by the fluid is given by Eq. (1).

$$W_1 = F_{\max} \times d \tag{1}$$

This stroke can be termed as the "drive" stroke. Now if the plate is made horizontal, a minimal force F_{min} would be necessary to pull the plate again to the left end position, through the same distance d, which constitutes what can be termed as the "recovery" stroke or the "feathering" stroke. The amount of work W_2 done by the plate on the fluid is given by Eq. (2).

$$W_2 = F_{\min} \times d \tag{2}$$

Since drive stroke force F_{max} is much larger than recovery stroke force F_{min} and the distance of travel d is same in both the cases, it can be concluded that the work done on the plate during the drive stroke is much greater than the work done by the plate during the recovery stroke i.e. $W_1 >> W_2$ and a net positive work is done on the plate.

Making the plate vertical again at the end of the motion to the left end causes the system to regain its initial state thus completing one cycle. In this cycle, if a small portion of W_1, equal to W_2, is used to complete the recovery stroke instead of providing it from an external source, the system can function independently generating net positive work by capturing energy from the fluid flow. Also since F_{max} and F_{min} are respectively the maximum and minimum forces that can be applied on a plate for a given flow, the generated net work W_{net} given by Eq. (3) could theoretically be the maximum work W_{tmax} also given by Eq. (3) that can be extracted from a fluid flow.

$$W_{tmax} = W_{net} = W_1 - W_2 \tag{3}$$

The complete cycle and its stages are illustrated in numbered order in Fig. 3.

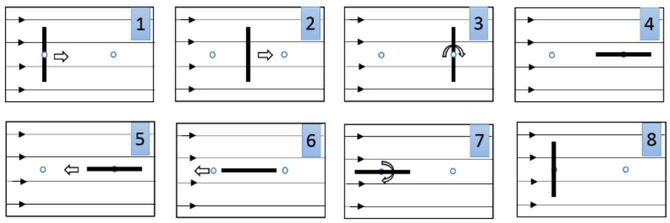

FIGURE 3. DIFFERENT STAGES OF THE CYCLE

MECHANISM

The linear to and fro motion described above requires a quick reversal in the direction of motion of the place which involves a loss of momentum since the plate would have some mass. The linear motion of the plate can be substituted by a simpler rotary motion as shown in Fig. 4 to still achieve a very similar result. This switch, while also conserving momentum, simplifies the device as well as the mechanism required to achieve the pitching motion. For the rotary system, there exists an axis of rotation and the plate would travel along with the flow (downstream) for 180 degrees of rotation about that axis and would travel against the flow (upstream) for the remaining 180 degrees of rotation. According to the principle discussed, the plate would be vertical and capture energy (drive stroke) while travelling downstream and then rotate by 90 degrees to become horizontal and have minimum drag (recovery stroke) while travelling upstream as shown in Fig. 5. Transitioning from one side of an imaginary plane shown in Fig. 5 to the other side for a plate in a rotary system is analogous to reversing the direction of motion for a linear system.

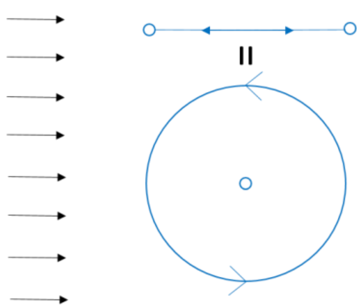

FIGURE 4. LINEAR AND ROTARY CYCLES

For the new rotary system, the plate needs to rotate by 90 degrees twice per cycle i.e. once each at the end of drive and recovery strokes. The consecutive rotations can either be in a same direction or in opposite directions as it would have little effect on the resulting state. This is because rotating a plate by 90 degrees twice and rotating by 90 degrees in a certain direction and then rotating it back by 90 degrees results in a similar configuration for a flat plate.

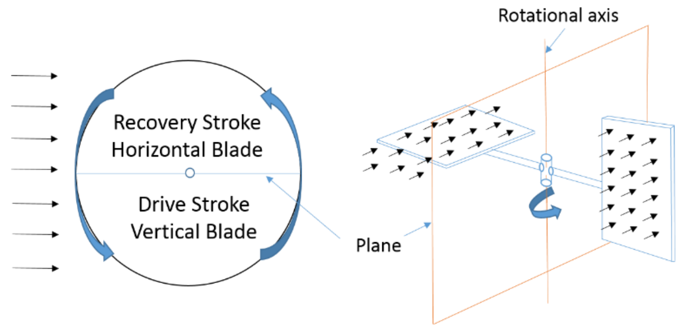

FIGURE 5. STROKES IN A ROTARY CYCLE

A slightly similar functioning mechanism is found in helicopters which use a device called swash plate, shown in Fig. 6, to regulate the pitch of their blades. It has two circular discs which can be tilted about any planar axis passing through their center. The lower disc only tilts while the upper disc also rotates along with the blades. The upper disc has levers connected to the blades through a crank. When the lower disc is tilted, the upper disc also tilts and one half on their surface is elevated while the other half is lowered. The levers on the upper disc rotate from the elevated side to the lowered side and then again to the elevated side in continuous cycles. While a lever is shifting to the elevated side of the disc, it moves up rotating its crank which results in having an increased pitch on the respective blade. And while a lever is shifting to the lower side, it moves down rotating the crank in an opposite direction resulting in having a decreased pitch by the same amount on that blade. So each blade experiences a reversal of the pitch about a mean position as its lever moves from the elevated side to the lowered side i.e. for every 180 degrees of rotation. The blades with increased pitch produce more thrust than the blades with reduced pitch and this difference in thrust is the reason a helicopter can pitch forward or backwards and roll to the left or right according to the input from the pilot. And the maximum pitch angle attained by each of the blades in each cycle is proportional to the angle by which the discs are tilted.

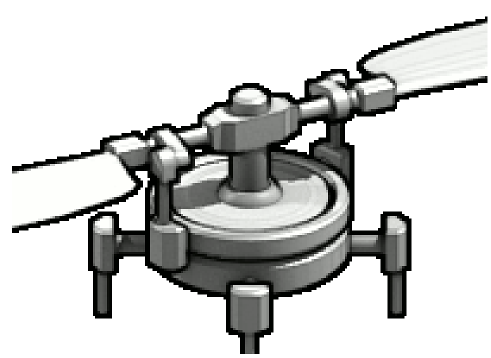

FIGURE 6. SWASH PLATE [8].

In this case the blades are being tilted in a cyclic fashion to obtain differential lift about the pitch or roll axis to perform the functions of pitching or rolling but not to capture energy. Also the reversal in pitch is not quick but takes place continuously over the 180 degrees of rotation about the vertical rotor axis which is not what is required in our case. But it can be understood that if pitch reversals can be performed at such high speeds in helicopter rotors, it can also be performed in our case where the cycle frequency would only be a fraction of that of helicopter rotors.

Swash plate converts linear input into rotary output by a continuous pitch variation spread uniformly over 360 degrees of rotation of a blade. But since we need quicker rotations which must happen when the blade is changing from upstream to downstream position and vice versa, a modified swash plate is used. Abrupt plate motions might result in vibrations and create shock waves in the fluid around the plate and hence are avoided. Since the blades of the turbine experience pitch variations in a cyclic manner, the turbine is termed as Cyclic Pitch Turbine.

DEVICE

After establishing the principle and the mechanism, the following parameters were selected to fabricate a prototype for initial testing. Number of blades for the device is selected to be three to keep the design simple and since at least one blade has to be in the power stroke at all times. A device with less than three blades might not at all be functional and the power output would not be reasonably uniform as a large difference would exist between the peak power and the minimum power generated in one cycle. So a three bladed design is selected as a compromise between simplicity and uniformity in power output.

The blades as described above are thin, rectangular plates. Though rectangular profile may not be the optimal shape for the blades, it is being used for simplicity and ease of analysis and comparison with other drag based VAWTs. All the required parts are fabricated and assembled to form the first prototype. Fig. 6 shows a solid model of the fabricated prototype.

FIGURE 6. SOLID MODEL OF THE PROTOTYPE

Fig. 7 represents top and isometric views which depict how a full scale working model of the turbine might look and function.

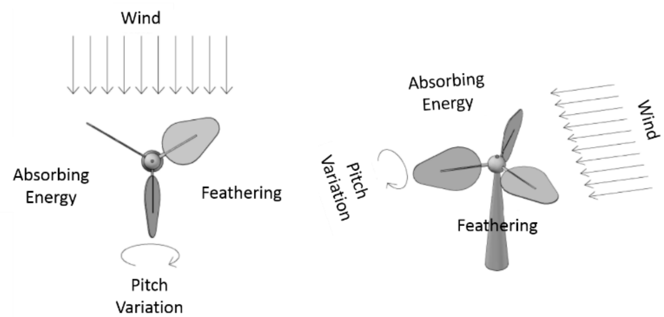

FIGURE 7. TOP & ISOMETRIC VIEWS OF THE TURBINE

EXPERIMENTS

The principle seems to be simple and by intuition would seem to work as expected. But the real fluid motion across the turbine could be complex and the ability of the turbine to capture energy could only be corroborated through experimental investigations.

Experiment – 1

Experiment one comprises of simply suspending the turbine in a fluid flow to observe if the device even works. The turbine is tested by suspending it front of an air blower and then in a water tunnel by means of a two columns that support the turbine in the precise position with respect to the flow.

Observation

As soon as the device is rightly positioned in the fluid flow, the blades start to rotate, about the vertical axis, while performing the pitching motions in the horizontal plane as is expected to do thus proving the functionality of the device.

Experiment – 2

The purpose of the second experiment is to quantify the energy being captured and observe how factors like fluid flow rate and load on the turbine changes the rate of energy being captured. Since the water flow rate is very low and the turbine is rotating at a very slow rpm, the power generated is very low as well. Hence a very sensitive dynamometer is built to quantify the energy being captured. It uses a small DC motor as a generator coupled to the driven shaft of the turbine through a step up gear box that increases the rpm by a factor of close to 50. The generator has a rheostat connected to it to change the load on the turbine. The resistance offered by the rheostat is inversely proportional to the load on the turbine and hence the torque developed by the turbine. This relation is explained by Eq. (4) and Eq. (5).

$$V \div R = I \quad (4)$$

Where

V is the voltage generated
R is the resistance applied
I is the current through the circuit

$$T = k_T \times I_a \times Ø \quad (5)$$

Where

T is the torque on the motor

K_T is a constant

I_a is current

Ø is magnetic flux

An ammeter is connected in series to the rheostat to measure the current being generated and the applied resistance is noted. The ammeter is also connected to an acquisition system to record the measurements. Averaging the ammeter readings over an extended period of time gives a value very close to the mean current *I* being generated. The average power being generated *P* is calculated from Eq. (6).

$$P = I^2 R \quad (6)$$

The first part of the second experiment is to observe the relation between the fluid flow rate and the power it generates. The fluid flow rate is varied by increasing the speed of the pump that is causing the flow. The pump speed is increased in steps and in each step, 500 readings of the current being generated are recorded.

The second part of this experiment is to observe the relation between the load on the turbine and the power it generates. The load on the turbine is varied changing the resistance in steps. And at each step the current readings are recorded for 500 seconds.

Observation

An almost linear increase is observed in average power value with increase in the pump speed control reading implying that an increase in flow velocity increases the power output of the turbine. The graph between average power generated and the pump control reading is shown in Fig. 8.

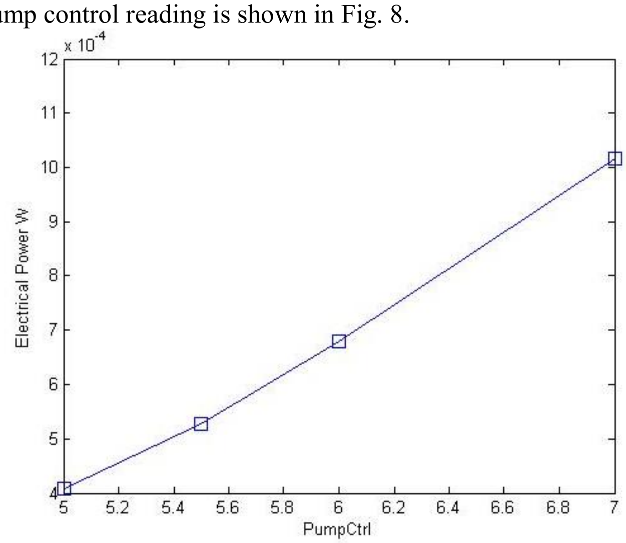

FIGURE 8. POWER OUTPUT VS PUMP CONTROL GRAPH

Examining the value of the average power generated and the value of resistance applied through the rheostat shows that there exists an optimal load value at which the turbine generates maximum power. The average power generated at other values of resistance, which is inversely proportional to the torque generated by the turbine, is less than at that optimum resistance. The graph between the average power generated and the resistance applied through the rheostat is shown in Fig. 9.

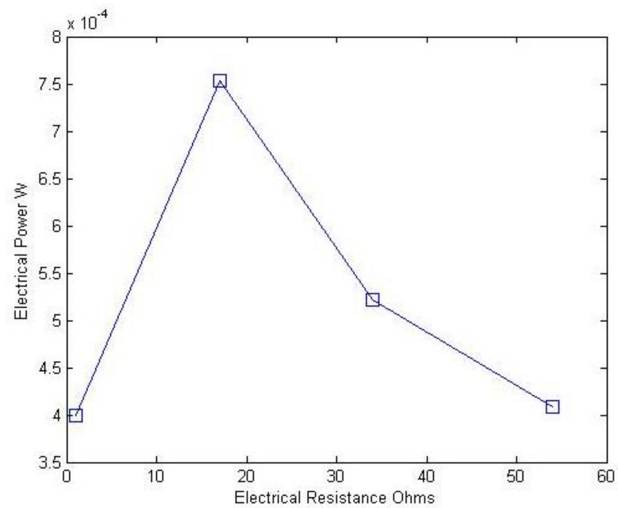

FIGURE 9. POWER OUTPUT VS ELECTRICAL RESISTANCE

COMPUTER SIMULATOIN

A computer simulation is run to compare this Cyclic Pitch Turbine to a Savonius Turbine. The simulation is at the most basic level by comparing the aiding drag force and the adverse drag force at only one static position of the Cyclic Pitch turbine with the Savonius turbine.

From the simulation, the static net aiding force in the Cyclic Pitch turbine is found to be very similar to the Savonius turbine. It is known that with increase in Savonius turbine rpm, the adverse drag increases while the aiding drag decreases considerably. And in our turbine, the aiding drag reduces but adverse drag remains almost the same which is the reason why this turbine is likely to surpass the efficiency of the Savonius turbine at even small fluid velocities.

THEORETICAL OBSERVATIONS

To compare the simulations with experimentally achieved data, drag coefficients were compared for flat plate, open and closed cylinders which are used in Savonius turbines. The drag coefficient [9, 10] for a flat plate is compared to the difference between the drag coefficients of open and closed cylinders. It is observed that the net drag coefficient for a cylinder is almost equal to the drag coefficient of a flat plate. Thus it can be said that even when a Savonius turbine and the cyclic pitch turbine are stationary, the force propelling both turbines are similar which is the same result obtained from the simulation.

CONCLUSION

The experiments show that the cyclic pitch turbine has the characteristics of conventional turbines. It has an increased power output for faster fluid flows and it has an optimal load value for maximum power output. Also when comparing it with other drag based VAWTs, it is apparent that the adverse drag force, which reduces the power output by a large amount, is considerably reduced. Although further work is needed, preliminary results show that this turbine is likely to have a better efficiency as also indicated by the simulations. Future work will involve a range of power measurements and experiments comparing it with similar technologies to show its full capabilities.

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