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PERFORMANCE ANALYSIS OF HIGH ALTITUDE TWO-DIMENSIONAL TETHERED PARA GLIDERS WIND ENERGY GENERATION

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ABSTRACT

Recently designed wind energy systems use large traction kites to drive electricity generation equipment at ground level; this exploits stronger and more consistent winds available at higher altitudes than used by traditional wind turbine systems. These kites require active control. In this paper, a kite power generation system composed of a seesaw mechanism controlled by springs and swivel mechanism has been developed which drives the shaft of the generator continuously in a power cycle. Considering the effects of air resistance on the kite movement, an air pump has also been used to give lift to the kite. This new technique generates power in a cycle by rotating the shaft connected to the rollers by means of roller chains, which in turn are connected to winches and then to seesaw mechanism by means of tethers. It has been observed, from the comparison of this techniques with wind turbine power generation system for the same average wind velocity, that the overall cost of the kite power generation is almost 50% cheaper than that of wind turbine power generation as power output of kite power generation system is almost double that of wind power generation system for the same. Hence, it has been concluded that the kite power generation technique has been found to be also best suitable for generating power compared to wind turbine system for developing countries too.

Keywords: High-altitude Wind Power Generation, Swivel Mechanism, Seesaw Mechanism, Para gliders

I INTRODUCTION

Wind energy is considered as an ideal renewable energy source, since it is infinitely sustainable and clean. The current wind power plant technology can reach and extract only a small part of the wind energy. A conventional wind turbine is a machine that converts wind's kinetic energy into electrical energy through a rotor coupled with an alternator. These turbines have a number of advantages as they do not require fuel and produce neither toxic nor radioactive wastes. However, these huge constructions are fixed and limited. The maximum height of such a wind turbine is limited to 200m where the wind is still unstable with an acceptable speed. In fact, the kite powered system can be implemented in areas with larger variations in wind velocity as the kite has the ability to reach much greater altitudes. The research for stronger and more regular winds led to the birth of several solutions such as balloons, airborne wind turbines and tethered airfoils (kites). The principle of the balloon, developed by Magenn Power Inc. involves a helium-filled balloon stationary at a height of 200m to 350m rotates around a horizontal axis connected to a generator. The energy produced is transmitted to the ground by a conductive tether.

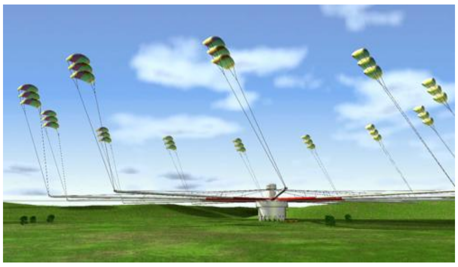

Fig 1: KiWiGEN Design

The second solution offered by Sky WindPower, Joby energy or Makani Power (funded by Google), would be to use airborne wind turbines to harness energy directly in high-altitude winds and to send it to the ground by cables. But this system has some technical complexities and high cost with a significant risk related to its weight. The third option is to use power kites as renewable energy generators such as the ”Kite Wind Generator” of Politecnico di Torino and ”Laddermill” of the Delft University of Technology. All these constructions have practically the same operation principle, which is to mechanically drive a ground-based electric generator using one or several tethered kites. Energy is extracted from high altitudes by controlling the kite to fly around a lying-eight orbit with high crosswind speed. This develops a large pulling force that turns the generator, thus generating electricity. However the kite should be always redrawn to its initial position once after reaching maximum height, which consumes some energy by doing so. The main objective is to improve the recovery cycle using this new mechanism which aids in continuous production of the power. In this paper, various models on kite power generation are studied.

II LITERATURE SURVEY

Kite power is a centuries-old concept now made practical. Innovations in aerodynamics, fabrics, and flying line have spawned a generation of powerful and maneuverable kite "engines" flown for sport and pleasure. In late 70’s during the oil crisis, the kites were used for energy production. However, when oil prices decreased again, the research of kite wind generators stopped quickly and there were only some publications.

The most significant of those publications (Loyd, 1980) which introduces the basic idea of the kite power plant and some results about kite speed and power. In the 21th century some research groups are again interested in the idea of extracting energy from high altitude winds with kites. This idea seems now so promising that these groups have been researching continuously for many years with excitement, and also several newly-found companies have started developing and testing kite power plant prototypes. Nowadays there are lighter and stronger kite fabric and line materials available.

The increasing popularity of Para gliders and power kites as hobby equipment has made kites more common. Modern electronics and computer technology have made real-time optimization and automatic remote control a lot easier and cheaper. These and other changes in conditions and new enabling technologies have now made kite wind generators maybe the most promising concept for extracting energy from high altitude winds.

There are already several working small-scale prototypes using power kites that have demonstrated the feasibility of the concept at least in small scale. From these prototypes the KiteGen prototype presented in publications (Canale et al., 2006) and (Canale et al., 2007) has a similar working principle and they also present some estimations of power from computer simulations.

III VARIOUS PROPOSED KITE POWERED GENERATION MODELS

Dr. J. S. Goela was one of the first people to investigate the feasibility of using kites to harness wind energy. Goela investigates a system in which the back and forth motion of a kite would be converted into up and down motion of a bucket in a deep well. He determined steady state equations of a kite in the air to determine line tensions and power output (Goela, 1983). In order to get optimal power and kite flying reliability, Goela's team proposed many different kite designs.

The mechanism proposed by Dr. Goela's team was designed to lift a bucket from a deep well using a kite. The design incorporated a balanced beam on a fulcrum with springs attached to one end of the beam. These springs were used to change the angle of attack of the kite, causing the arm to ascend and descend (Goela, 1983). A schematic of this design is shown in Figure 1.

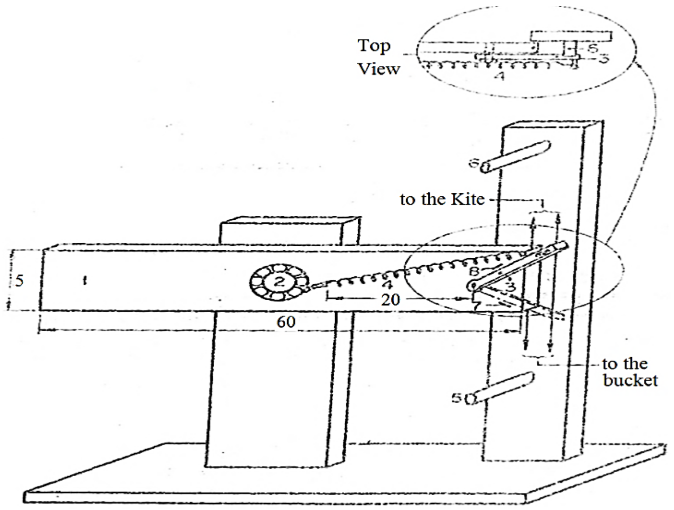

Fig.2: Details of a kite pump mechanism (All dimensions are in mm)

David Lang (Lang, 2005) investigates several different schemes for kite power generation and determined the most feasible designs. Lang compares six different design configurations using a detailed decision matrix. Each design was rated on a number of criteria and the best were determined to be the best options. The two highest scoring designs were the Reel‖ and the KiwiGEN.‖

The Reel design, as shown in Figure 2, involves harnessing the energy from the kite as it is pulled out and wound back in. The energy is harnessed using a series of mechanical and electrical components.

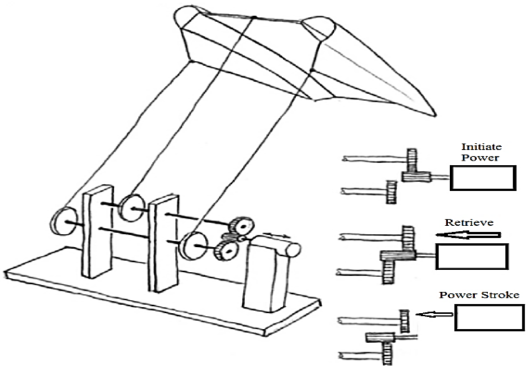

Fig.3: Reel Design

Kite Gen Research is a company that is developing new technology to harness wind energy. Their goal is to create a new kind of power plant, which operates at a cheaper cost and generates equivalent power to current power installations. When completed, it is estimated that KiteGen will produce one Gigawatt of power for the cost of 1.5 Euros per megawatt hour, which is significantly cheaper than the current 43 Euros per megawatt hour (Martinelli, 2008). They use the high wind speed of the troposphere (lower atmosphere, 800–1000 meters) to power their kites, which in turn are hooked up to and rotate the central structure, generating power. The positions of the kites are monitored and controlled by very sophisticated sensors in order to optimize energy generation (Kite Gen, 2007). Figure 4 shows a concept rendering of the system.

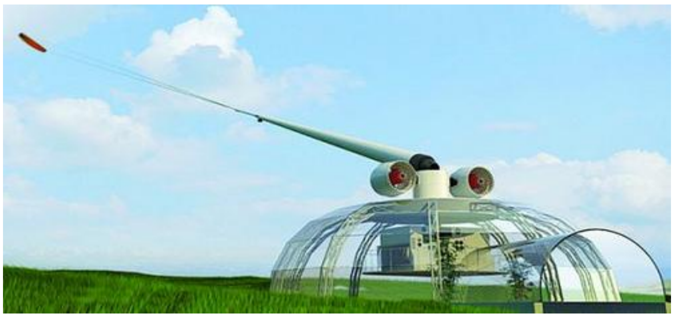

Fig.4: KiteGEN Design

The conversion of mechanical energy to electrical energy will require the use of a mechanically driven electrical generator. However, there needs to be a mechanism that can convert the oscillating motion of a kite into rotary motion that can power a generator. Several possibilities for such a mechanism were considered.

IV VARIOUS CONVERSION MECHANISMS

4.1 Simple Lever Mechanism

A simple lever, a simplest conversion mechanism, would be a beam attached to a kite that would spin around a shaft powering an electrical generator as shown in Figure 5.

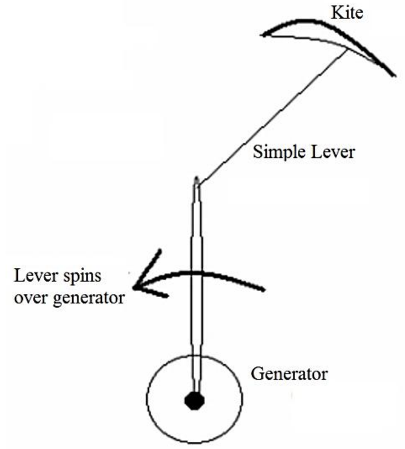

Fig.5: Simple Lever Mechanism

The major advantage of this system is simplicity of construction. However, this system was found to have several disadvantages. One major disadvantage is the system's inability to have the simple lever to rotate in a complete circle. The shaft would require enough momentum to keep revolving, while the kite would need to be put into "de- powered" and "Powered" positions at key points in the revolution of the lever. This turns out to be an extremely difficult task.

4.2 Simple Lever Reverse Clutch Mechanism

In this mechanism, as shown in Figure 6, the kite would move the lever from side to side. The end of the lever attached to the generator shaft would also be connected to a reversing clutch. This clutch would make sure that the motion of the generator shaft only moves in one direction. An advantage of this system is that the lever does not need to completely revolve around the entire assembly. The angle of attack would change moving the lever from one side to the next. However, a concern with this system is that it cannot sweep enough of an arc to have the lever cause any significant torque upon a gear system.

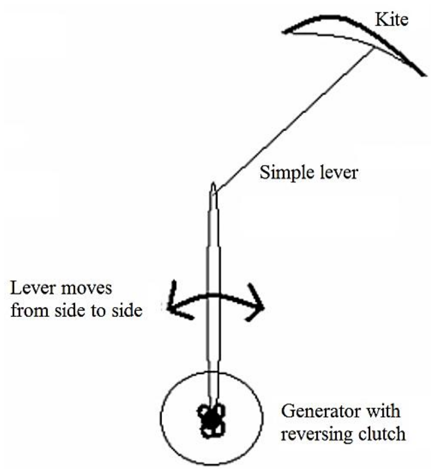

Fig.6: Simple Lever Reverse Clutch

Another possible mechanism consisted of a two-kite system. The two-kite system involves two kites that work together to move the shaft of the generator. This can be accomplished in several ways. Two kites could run the reversing simple lever mechanism as shown in Figure 6. Two kites could also be made to move in a circular motion that could power a generator as shown in Figure 7.

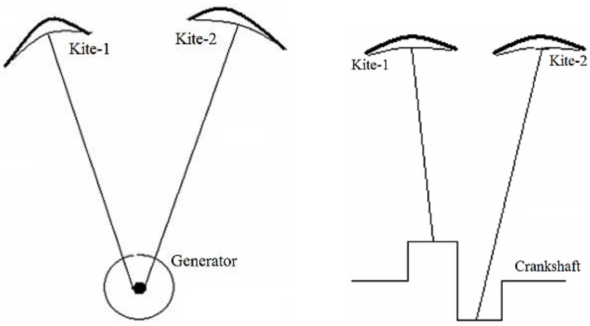

Fig. 7: Possible 2-Kite System-1 Possible 2-kite System-2

The difficulty of the two-kite system is the added complexity. The kites could move around each other and twist together. It also becomes more complex to control the motion of the kite. If the two kites aren’t configured properly their motions could counterbalance each other.

4.3 Oil Pump Jack

There are also several classical mechanisms that have been used to convert oscillating motion into rotary motion and vice versa. One of these mechanisms is the pump jack. The pump jack is the mechanism used to pump oil from oil wells. An example of a pump jack is shown in Figure 8. In the case of the pump jack, a motor creates a rotary motion the moves the left side of the beam up and down, causing the right side of the upper beam to move up and down in an oscillating motion. In the case of our project, the up and down motion of the kite would move the right side of the pivoting beam up and down which would then drive the beam that causes the rotary motion. This rotary motion would then drive the generator.

Fig. 8: Oil Pump Jack

4.4 Sprag Clutch

Other possible mechanisms involve the use of spring systems. This spring systems would rely on the use of a sprag clutch. A sprag clutch is the mechanism that allows a ratchet to apply a force in one rotational direction and not in the opposite direction. An example of a possible system using a sprag clutch can be seen in Figure 9.

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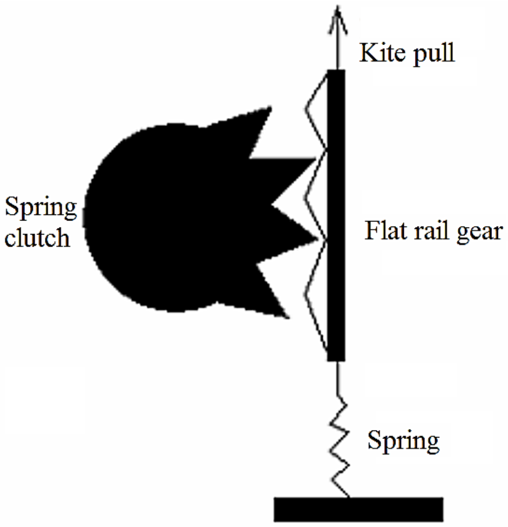

Fig.9: Example Sprag Clutch

In a sprag clutch system, the kite would pull the flat rail gear that is positioned to move up and down. When the kite is put into the power mode, the kite would lift the rail upward, turning the large round gear and eventually spinning an electrical generator. When the rail gear reaches a maximum height, the kite is triggered to change into "de-power" mode. Once this happens the kite loses its upward pull and the spring pulls the kite along with the rail gear back down into the starting position. As the gear rail moves downward the gear moves back down but does not affect the gear shaft motion. When the kite reaches the starting position, the kite is triggered into power mode and the cycle starts all over again.

4.5 Pumpjack / Sprag Clutch Combo

The last possibility considered was the combination between sprag clutch and large rotating beam found on the pump jack. The idea is that a kite would be attached to an oscillating balanced beam. When the kite was in the down position it would increase the kites angle of attack and the beam would be lifted upward by the kite motion. When then beam reached the top of its arc, a sliding weight inside the rotating beam would pull the angle of attack control strings downward, decreasing the kites angle of attack. The weight within the beam would then pull the beam back down to starting position. The Sprag clutch will come in to play when the beam is in its upward trajectory. While the beam is moving upward it will be pulling a chain which is spinning a sprag clutch that in turn leads to a gearbox and eventually a generator. A schematic of this is shown in Figure 10.

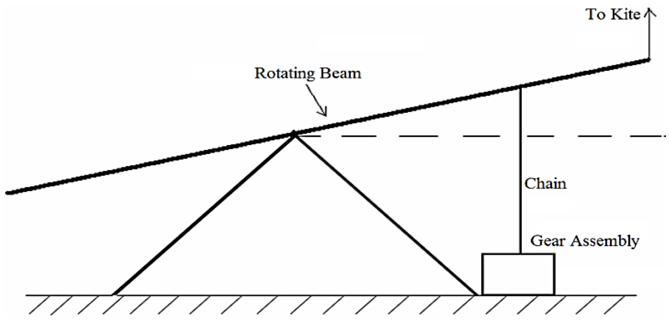

Fig.10: Pump jack / Sprag Clutch Combo

V DEVELOPMENT OF NEW DESIGN

A new system is being developed which overcomes the problems in the above mentioned systems. The basic idea of using seesaw mechanism is, if one kite is in power phase then the other kite will be in depower phase. So that the generator shaft rotates continuously and the electricity is generated. A basic idea of this design is shown in Figure 11.

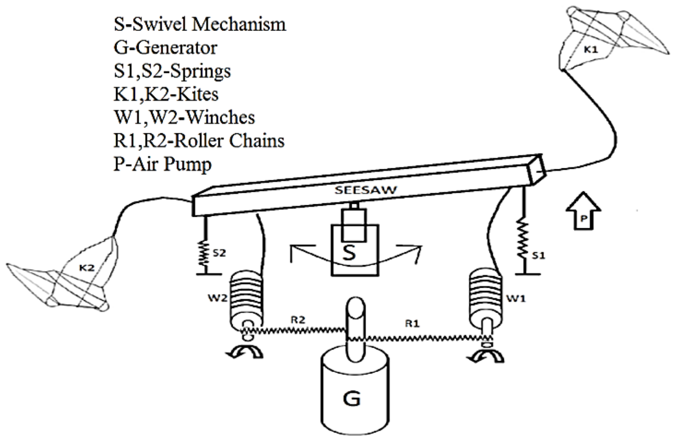

Fig.11: New design using seesaw mechanism

The winch which controls the length of the tether by pulls in and pulls out the tether. The drum is the one that is manually controlled, i.e., a lot of man power is utilized. So, a winch is preferred rather than a using a drum.

A kite requires some initial air force in order to set the kite into motion. Air pumps are used to fulfill the initial requirement. Whenever the kite reaches maximum height there the wind will be in constant and it is difficult to raise the kite further heights. A spring attached to the seesaw in the above Figure retracts the seesaw to its original position due to its own elastic properties. Roller chains are most efficient in transmitting the motion in one direction only. So, these are considered in this system.

VI OPERATING PROCEDURE

Initially the first kite "K1" is set in motion using external air pump. While the kite is in motion the right part of the see-saw moves upwards and stretches the spring "S1". To loosen the tether winch rotates in anti clock-wise direction and transmits this motion to generator through a roller chain system. Once the kite K1 reaches the maximum height, due to the spring's elastic property it retracts the motion and Kite K2 moves upwards and the cycle is repeated. From the earlier observation in a cycle one power phase and one depower phases are observed. Whereas in this model we can obtain two power phases in one cycle only. By this technique the overall power produced in a cycle can be optimized. In general, the see saw mechanism may limit the horizontal motion of the kite. A 360^0 motion is to be provided to the seesaw in order to eliminate the drag force on the kite. So, Swivel mechanism is included to avoid this.

VII COMPONENTS USED IN THE NEW SYSTEM

Kites

Kites usually used in this system are large kites, also known as Para gliders. Para gliders are constructed using different types of sailcloth, line material, and webbing. The glider itself is usually made from rip-stop nylon produced by one or more manufacturers. Different weights (g/m^2) of material are used for the top and bottom surface, as well as the ribs and reinforcement points in the glider. Different fabric manufacturers produce fabrics with different strengths and weaknesses. Almost all of these fabrics have some sort of UV coating to increase longevity.

Kite modeler software proposed by the NASA to study the physics and math describes the flight of kite. In this software, several types of kites and different shapes, sizes, and materials can be chosen to design the kite. Also the values of different variables which affect the design can be changed and new flight characteristics can be seen. The program tells whether the design is stable or not and also computes a prediction of how high the kite can fly.

By using this software the best economic design is selected as shown in the Figure 12.

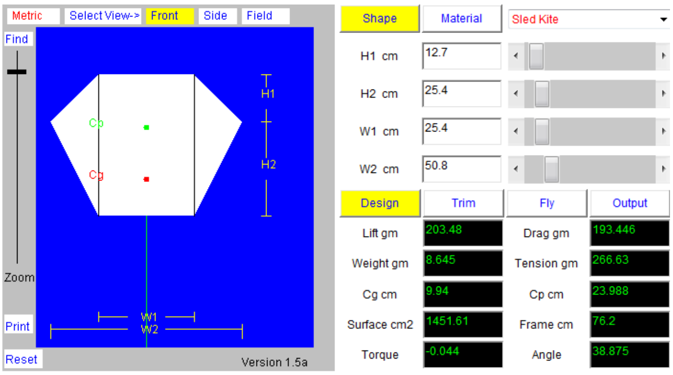

Fig. 12: Kite Modeler Software

Kite's lift equation:

$$L = C_l \times A \times r \times 0.5 \times V^2$$

Where,

C_l–Coefficient of lift = $2 \times \pi \times a$

A–Projected surface area (m^2)

r–Air density (kg/m^3)

V–wind velocity (m/s^2)

a–Angle (radians)

Tether

The lines can be made from either Kevlar (aka Aramid), or Spectra (aka Dyneema) in various diameters measured in mm as shown in Figure 13. Kevlar seems to be the material of choice for most glider manufacturers; however, some glider companies choose to use Spectra as an alternative. Spectra line is about 40-percent stronger than Kevlar, but it does tend to shrink over time or when it has been exposed to water, thus

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requiring maintenance. Lines are made up of a core that provides the strength, and a sheath that provides UV exposure and abrasion protection. The core is either Kevlar or Spectra, and the sheath is usually made of polyester. The lines connect to the glider at attachment points that are reinforced with Mylar, and at the other end to risers via triangular quick links made of stainless steel. The risers are generally made from pre-stretched nylon.

Fig. 13: Tether Lines

Winches

As shown in Figure 14, a winch is a mechanical device that is used to pull in (wind up) or let out (wind out) or otherwise adjust the "tension" of a rope or wire rope (also called "cable" or "wire cable"). In its simplest form it consists of a spool and attached hand crank. In larger forms, winches stand at the heart of machines as diverse as tow trucks, steam shovels and elevators. The spool can also be called the winch drum. More elaborate designs have gear assemblies and can be powered by electric, hydraulic, pneumatic or internal combustion drives. Some may include a solenoid brake and/or a mechanical brake or ratchet and pawl device that prevents it from unwinding unless the pawl is retracted.

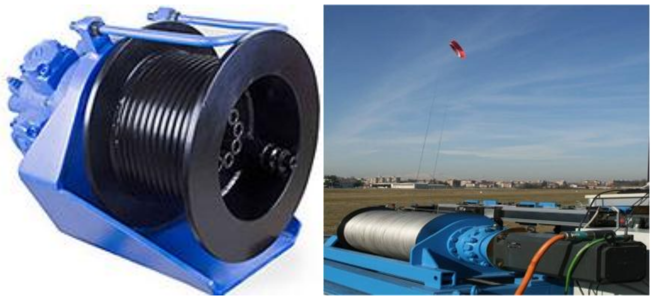

Fig. 14: Winch Mechanism

Generator

The generator, or alternator, transfers the mechanical energy of the kite arm mechanism into electrical energy. It transforms the rotational energy of the rotating shaft and turns it into electricity. Cost and capacity were the major functions in determining the choice. After comparing several alternators we were able to determine which would be the best choice for this project. Wind blue’s model 512 permanent magnet alternator, shown in Figure 15, was chosen as it can produce the desired electrical output of one kW of electricity within adequate rpm values (~2000) and has a very reasonable price.

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Fig. 15: Wind blue's model 512 permanent magnet alternator

Air Pump

A mechanical fan is a machine used to create flow within a fluid, typically a gas such as air. The fan consists of a rotating arrangement of vanes or blades which act on the air. The rotating assembly of blades and hub is known as an impeller, a rotor, or a runner. Usually, it is contained within some form of housing or case. This may direct the airflow or increase safety by preventing objects from contacting the fan blades. Most fans are powered by electric motors, but other sources of power may be used, including hydraulic motors and internal combustion engines. Fans produce air flows with high volume and low pressure (although higher than ambient pressure), as opposed to compressors which produce high pressures at a comparatively low volume. A fan blade will often rotate when exposed to an air stream, and devices that take advantage of this, such as anemometers and wind turbines, often have designs similar to that of a fan. In this project lift of the kites are achieved by air pumps.

Seesaw

A seesaw (also known as a teeter-totter or teeter board) is a long, narrow board pivoted in the middle so that, as one end goes up, the other goes down. Mechanically a seesaw is a lever and fulcrum. Seesaws also work as a simple example of a mechanical system with two equilibrium positions. One side is stable, while the other is unstable.

Swivel Mechanism

A swivel is a single central leg that allows the see saw to spin around as shown in Figure 16.

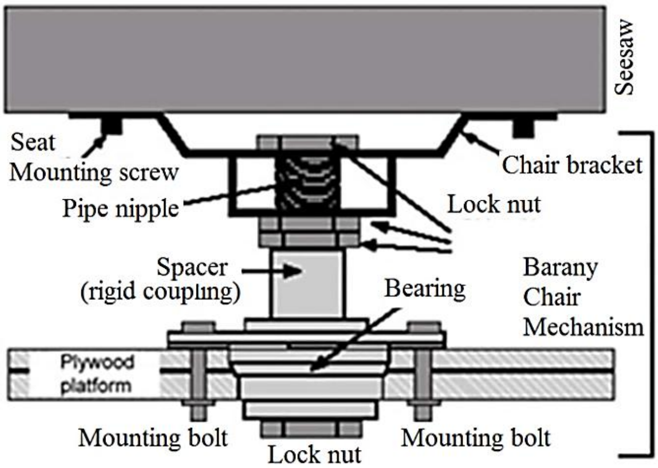

Fig. 16: Swivel Mechanism

Springs

A spring is an elastic object used to store mechanical energy. Springs are usually made out of spring steel. Small springs can be wound from pre-hardened stock, while larger ones are made from annealed steel and hardened after fabrication. Some non-ferrous metals are also used including phosphor bronze and titanium for parts requiring corrosion resistance.

VIII RESULTS AND DISCUSSIONS

Table 1: Cost estimation and comparison

Kite	Approx. Cost (Rs.)
Kite ($10m^2$) + Tether*	49,500.00
Power Conversion mechanism	44,000.00
Electronics, AC-DC Inverter Generator	1,10,000.00
Batteries$ (24V,9kWHr)	55,000.00
Accessories	27,500.00
Total	231,000.00

Wind Turbine#	Approx. Cost (Rs.)
Turbine + Generator	1,30,000.00
Tower (100 ft)	134,750.00
Electronics, AC-DC Inverter	99,000.00
Batteries (24V,9kWhHr)	55,000.00
Accessories	27,500.00
Total	458,700.00

*Based on prices from power sports, seabrook NH.

#Based on Bergey XL-I wind turbine rated at 20mph, 2.5 meter diameter rotor

$Battery storage (no connection to grid) assumed. Batteries and accessory systems identical since both the kite and wind turbine must accommodate variable speed operation.

Power output

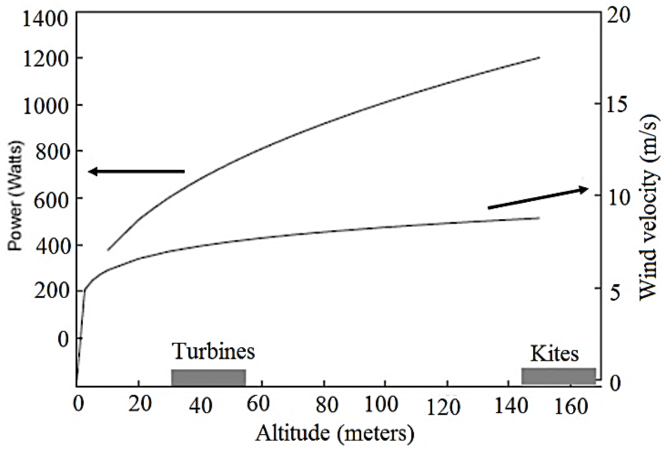

Fig. 17: Power Output & wind velocity for turbine and kite

The variations of power output and wind velocity of the turbine and kite ($10m^2$) with respect to various altitudes have been shown in Figure 17 and compared which gives the following information:

- As the altitude increases the power of kites are comparatively increased
- It is observed that at an average wind velocity of $10m/s^2$ the power output for the kite is in the range of 400W–600W whereas the power output of the turbine is 200W–400W.

IX CONCLUSIONS

From the results of comparison of kite and wind turbine power generation technologies, it is found that the overall cost of the kite power generation is almost 50% cheaper than that of wind turbine power generation as power output of kite power generation system is almost double that of wind power generation system for the same average wind velocity. Hence, it the kite power generation technique is also best suited for developing countries too. It is also concluded that this new technology of kite power generation system has more advantages when compared to a wind turbine power generation in many aspects.

X FUTURE WORK

A flywheel can be used which utilizes the power generated by the movement of seesaw alone i.e., kite motion is not included. So, this will be taken into consideration in the future works.

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