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Analysis and Simulation of Powerkite to Harness High Altitude Wind for the Generation of Electricity

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Abstract

High altitude wind energy (HAWE) is a new concept of renewable energy which has an increased attention since the last decade. Many ideas have been suggested regarding the concept of HAWE of which utilizing the power kites is one among them being the effective and efficient solution. The mechanical motion to the electric generator in the ground is provided by the power kite flying in the high altitude wind is the basic concept. This concept has the potential to overcome the limits of the present renewable technologies utilizing wind energy and can serve the global power crisis when used in larger scales utilizing less economy.

Keywords: *High-altitude wind energy, Wind energy, Aerodynamic coefficients, Wind power generation.*

1. Introduction

GLOBAL wind power has the potential to meet the world's energy demand and, differently from fossil sources, it is largely available almost everywhere. However, the actual wind power technology, based on wind towers, has several limitations that need to be overcome to make such energy source competitive against fossil sources (for an overview of the present wind technology, see, e.g.,[1]). In particular, wind towers require heavy foundations and huge blades, with massive investments leading to higher energy production costs with respect to thermal plants. Moreover, the average power density per km obtained by the present wind farms is 200–300 times lower than that of big thermal plants of the same rated power, leading to significant land occupation and impact on the environment. Finally, wind towers can operate at a maximum height of about 150 m, due to structural limits, and can therefore be used with profit only in locations with "good" wind speed at 50–150 m of height from the ground. Recent studies (see, e.g., [2] and [3]) have shown that these limitations can be overcome by the developing technology of high altitude wind power. The basic idea is to capture wind energy using tethered airfoils (e.g., power kites used for surfing or sailing) whose flight is suitably driven by an automatic control unit. Wind energy is collected at ground level by converting the mechanical power transferred by the kite lines into electrical power, using a suitable mechanism and electric generators. This class of power generators, which will be referred to as "KitePower" in the following, are able to exploit wind flows at higher altitudes (up to 1000 m), where quite strong and constant wind can be found basically everywhere in the world. Thus, this technology can be used in a much larger number of locations. Moreover, the strength of high altitude wind flows can be more effectively exploited, since the generated power grows with the cube of wind speed, leading to higher power values with respect to those of wind towers placed in the same location. Furthermore, the bulky structure of a KitePower is kept at ground level, while only airfoils and their lines move in the air: thus, the construction costs of this kind of generator are much lower than those of a wind mill of the same rated power (i.e., the level for which the electrical system has been designed, see[1]), since the structural problems, given in wind towers by unbalanced forces and masses at the tower's hub, are avoided by the system architecture in a KitePower. Finally, also from the point of view of system safety the KitePower shows quite big advantages, since the physical and economical damage given by the breaking of a kite or a line would be much lower than those given by the breaking of a wind tower. Due to all these reasons, it is expected that a KitePower will have a generated power density per kilometres squared much higher than a wind farm and much lower energy production costs, even lower than fossil energy.

2. The KitePower project

2.1 Basic concepts

The key idea of the KitePower project is to harvest high–altitude wind energy with the minimal effort in terms of generator structure, cost and land occupation. In the actual wind towers, the outermost 20% of the blade surface contributes for 80% of the generated power. The main reason is that the blade tangential speed (and, consequently, the effective wind speed) is higher in the outer part, and wind power grows with the cube of the effective wind speed. Thus, the tower and the inner part of the blades do not directly contribute to energy generation. Yet, the structure of a wind tower determines most of its cost and imposes a limit to the elevation that can be reached. To understand the concept of KitePower, one can imagine to remove all the bulky structure of a wind tower and just keep the outer part of the blades, which becomes a much lighter kite flying fast in crosswind conditions (see Fig. 1), connected to the ground by two cables, realized in composite materials, with a traction resistance 8–10 times higher than that of steel cables of the same weight. The cables are rolled around drum, linked to electric drive. An electronic control system can drive the kite flight by differentially pulling the cables (see Fig. 2). The kite flight is tracked and controlled using on–board wireless instrumentation to measure the airfoil speed and position, the power output, the cable force and speed and the wind speed and direction. Thus, the rotor and the tower of the present wind technology are replaced in KitePower technology by the kite and its cables, realizing a wind generator which is largely lighter and cheaper. For example, in a 2–MW wind turbine, the weight of the rotor and the tower is typically about 250 tons [5]. As reported below, a kite generator of the same rated power can be obtained using a 500–m^2 kite and cables 1000–m long, with a total weight of about 2 tons only [6].

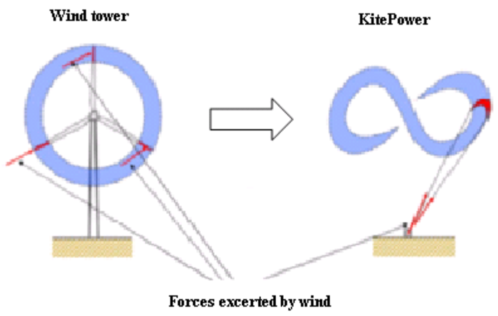


Fig. 1 Basic concept of KitePower technology.

The system composed by the electric drives, the drums, and all the hardware needed to control a single kite is denoted as Kite Steering Unit (KSU) and it is the core of the KitePower technology. The KSU can be employed in different ways to generate energy: two solutions have been investigated so far, namely the KP–yoyo and the KP–carousel configurations (see [4]). In the KP–yoyo generator, wind power is captured by unrolling the kite lines, while in the KP–carousel configuration the KSU is also employed to drag a vehicle, moving along a circular rail path, thus generating energy by means of additional electric generators linked to the wheels. The choice between KP–yoyo and KP–carousel configurations for further developments will be made on the basis of technical and economical considerations, like construction costs, generated power density with respect to land occupation, reliability features, etc. In this paper, the focus is on the analysis of the potential of KP–yoyo generators to operate together in the same site, thus realizing large KP–farms in terms of maximum and average generated power per km^2 and energy production costs.

2.2 KP–yoyo energy generation cycle

In the KP–yoyo configuration, the KSU is fixed with respect to the ground. Energy is obtained by continuously performing a two-phase cycle, *traction phase* and *passive phase*, in the traction phase the kite exploits wind power to unroll the lines and the generator driven by the rotation of the drums. During the *traction* phase, the kite is maneuvered so to fly fast in crosswind direction, to generate the maximum amount of power. When the maximum line length is reached, the *passive* phase begins and the kite is driven in such a way that its aerodynamic lift force collapses: this way the energy spent to rewind the cables is a fraction (less than 20%) of the amount generated in the traction phase.

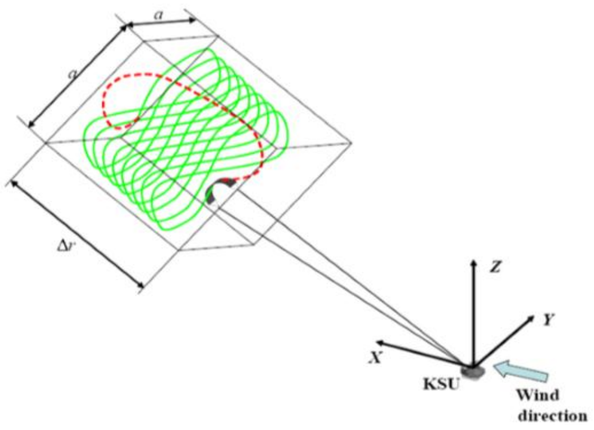


Fig. 2 KP-yoyo configuration cycle: traction (solid) and passive (dashed) phases.

3. KP-yoyo Wind Generator : Numerical and Simulation results

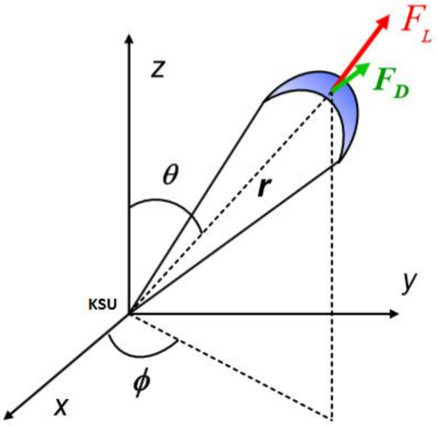


Fig. 3 Model diagram of a KP–yoyo.

$$F_L=\frac{1}{2}(C_L A\rho|W_e|^2) \qquad \ldots(1)$$

$$F_D=\frac{1}{2}(C_D A\rho|W_e|^2) \qquad \ldots(2)$$

*W*e: Kite speed wrt wind, *A*: Area of Area, ρ: Air density, *E*=C_L/C_D=Aerodynamic Efficiency, C_L: Lift Coefficient, C_D: Drag Coefficient.

3.1 Simplified theoretical crosswind kite power equations

Numerical simulations make it possible to evaluate the effects of wind turbulence on the system. However, simulation of the system via numerical integration takes a relatively large amount of time. Thus, a simplified static theoretical equation, giving the generated power as a function of the wind speed and of the kite position, is useful to perform first–approximation studies of the performance of a KP–yoyo and to optimize its operational parameters. Moreover, such an equation can be also used to optimize the operation of a KP–farm. The simplified theoretical equation is based on the following hypotheses:

- the airfoil flies in crosswind conditions;
- the inertial and apparent forces are negligible with respect to the aerodynamic forces;
- the kite speed relative to the ground is constant;
- the kite angle of attack is fixed.

Given these assumptions, the average mechanical power $P_{KP\text{–}yoyo}$ [6] generated by a KP–yoyo unit during a cycle can be computed as:

$$\overline{P}_{KP-yoyo} = \eta_e\eta_c C|W_x(\overline{Z})\sin(\theta)\cos(\phi) - r^{\cdot trac}|^2 r^{\cdot trac} \qquad \ldots(3)$$

Where

$$\overline{Z} = \cos(\theta)\,(\overline{r} + \underline{r})/2$$

$$C = \frac{1}{2}\rho A\overline{C}_L E_{eq}^2\left(1 + \frac{1}{E_{eq}^2}\right)\wedge\frac{3}{2}$$

$$E_{eq} = \overline{C}_L / C_{D,eq}$$

$$C_{D,eq} = \overline{C}_D\left[1+\left((2rd_l)\ C_{D,l}\right)/4A\overline{C}_D\right] \qquad \ldots(4)$$

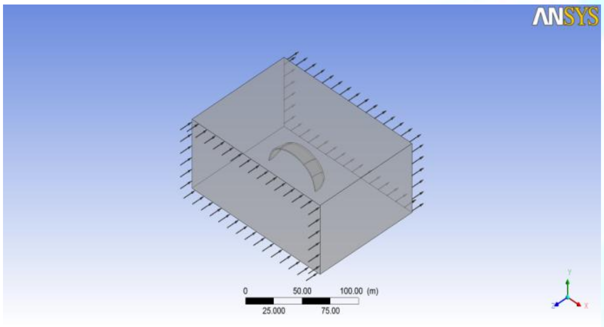
and

$\eta_c \in(0,1)$ is a coefficient accounting for the losses of the energy generation cycle of a KP–yoyo. r and r are the minimum and maximum values of the cable length during a KP–yoyo cycle (i.e. at the beginning and at the end of each traction phase respectively), while C_L and

C_D are the aerodynamic coefficients corresponding to the considered fixed angle of attack of the airfoil. Finally, $r^{\cdot trac}$ [6] is the line unrolling speed during the traction phase. The traction force generated on the lines can be also computed with a simplified equation as follows:

$$F^{c,trc} = C\,|W_x(\overline{Z})\sin(\theta)\cos(\phi) - r^{\cdot trac}|^2 \quad \text{...(5)}$$

3.2 Simulation analysis



According to the obtained simulation results, the controller is able to stabilize the system and the flight trajectory is kept inside a space region which is limited by a polyhedron of given dimension a×a×Δr (see Fig. 2). The value of 'a' depends on the kite size and shape, which influences its minimal turning radius during the flight: a minimal value of a≈5Ws has been assumed, where Ws is the airfoil wingspan. For example, it results that a 500m^2 kite is able to fly in a zone contained in a polyhedron with a = 300m. Δr is a design parameter which imposes the maximal range of cable length variation during the KP–yoyo cycle and it can be optimized on the basis of the airfoil and wind characteristics (see [6]). The control system is able to keep the kite flight inside the polyhedral zone also in the presence of quite strong turbulence (see [6]).

Simulation Of Power Kite

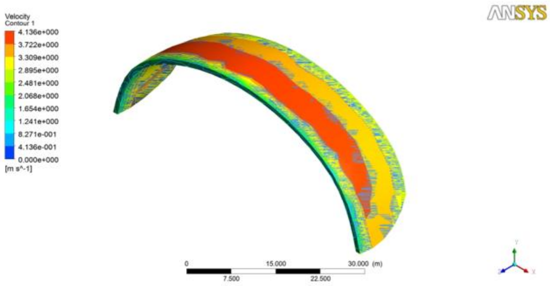


Fig. 4 Isometric view of the power kite under considerations of theoretical crosswind kite power equations.

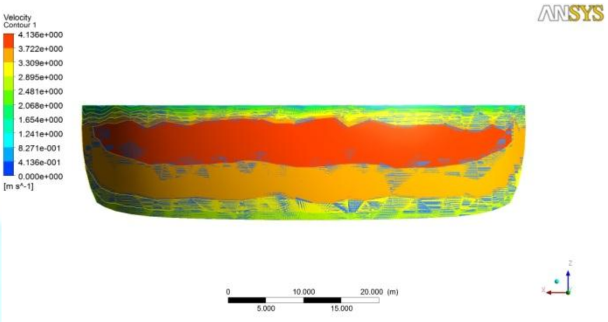


Fig. 5 Top view of the power kite.

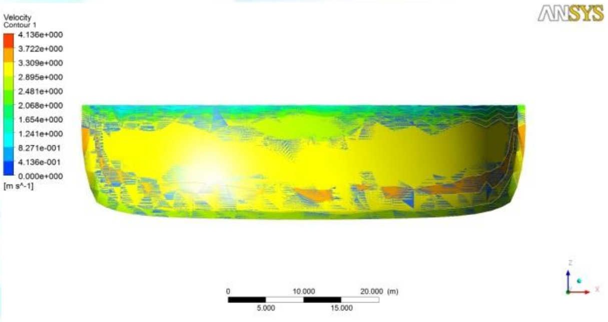


Fig. 6 Bottom view of the power kite.

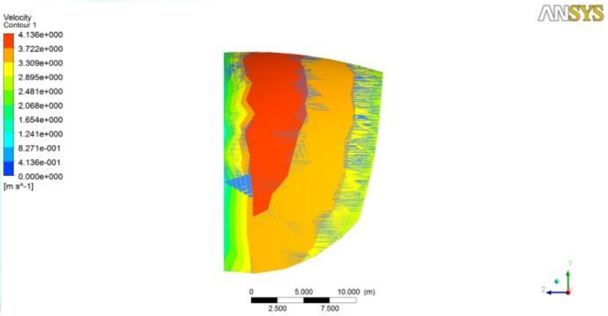


Fig. 7 Side view of the power kite.

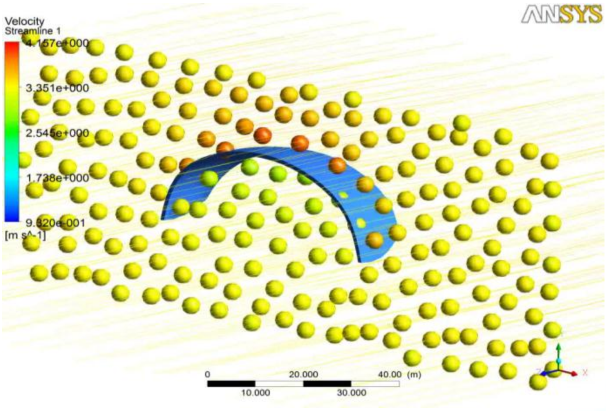


Fig. 8 CFX output showing effect of wind velocity around the power kite.

The aerodynamic characteristics considered for the simulations are those reported in Fig. 9. From such simulations, the power curve of the considered KP–yoyo has been computed (see Fig. 10): such a curve gives the generated power as a function of wind speed and it can be employed to compare the performances of the KP–yoyo with those of a commercial wind turbine with the same rated power (i.e. 2 MW), whose power curve (see e.g. [5]) is reported in Fig. 8 too. In particular, it can be noted that a net power value of 2 MW is obtained by the KP–yoyo with 9–m/s wind speed, while a commercial wind tower can produce only 1 MW in the same conditions. Note that the power curves are saturated at the rated value of 2 MW, corresponding to the maximum that can be obtained with the employed electric equipment. Moreover, for the KitePower a cut–out wind speed of 25 m/s has been also considered, as it is done for wind turbines for structural safety reasons, though it is expected that a KP–yoyo could be able to operate at its maximal power with wind speeds up to 40–50 m/s.

Table 1: KP-yoyo model parameters employed in the numerical simulation and in equation (5).

Kite mass (kg)	*m*	50
Characteristic area (m^2)	*A*	500
Base angle of attack (°)	α_0	3.5
Diameter of a single line (m)	d_l	0.03
Line density (kg/m^3)	ρ_l	970
Line drag coefficient	$C_{D,L}$	1.2
Minimum cable length (m)	$\underline{r}$	550
Maximum cable length (m)	$\bar{r}$	600
Air density (kg/m^3)	ρ	1.2
Average kite lift coefficient	C_L	1.2
Average kite drag coefficient	C_D	0.089

Numerical simulations have been also employed to investigate the dependence of the mean generated power on the kite area and efficiency, on the average cable length during the cycle and on wind speed. In the performed simulations, if not differently specified, a kite with the characteristics of Table I have been considered. Note that in all the simulations, the cable diameter has been dimensioned in accordance with the traction force exerted by the kite, which vary with the different considered parameter values.

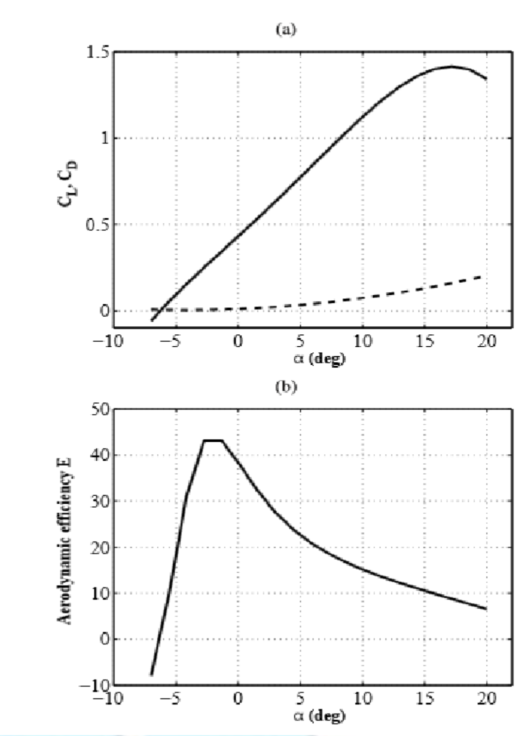


Fig. 9 (a) Kite Lift coefficient C_L (solid) and drag coefficient C_D (dashed) as functions of the attack angle'α'. (b) Aerodynamic efficiency E as function of the attack angle 'α'.

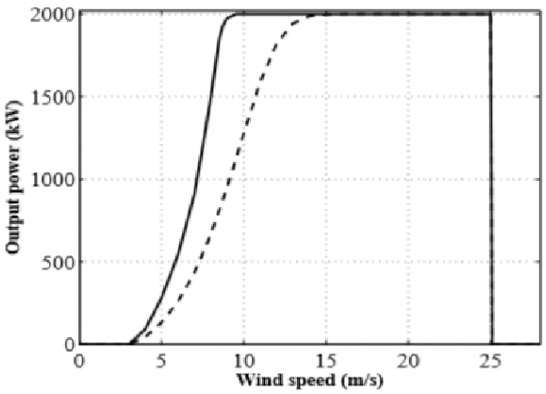


Fig. 10 Comparison between the power curves of a typical wind tower (dashed) and of a KP–yoyo (solid), both with the same rated power of 2 MW.

4. Conclusion

From the analyses and the numerical simulations, it is estimated that the power density of KitePower project is 8-13 times greater than that of present wind energy technology. The present wind energy technology could not utilize wind at high altitudes where the stable and constant wind is observed. Still the cost of tower and rotor blades become a limiting factor to harness the wind at high altitudes for present wind energy technologies. The stronger towers and the heavy rotor blades are replaced by the light weight composite cables and the simple power kite respectively. Also, the land occupation can be completely eliminated and the location of station can be selected at any place. Ultimately, the maintenance cost remains same for both the wind energy technology.

5. References

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