Offshore High-Altitude Wind Energy Using Controlled Airfoils

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Abstract:

This paper investigates the offshore application of an innovative high-altitude wind energy technology. The idea is to exploit the automatic flight of tethered airfoils (e.g. power kites) to extract energy from wind flows blowing between 200 and 800 meters above the sea. The key points of such a technology are described and the related operational parameters are optimized in order to maximize the generated power while satisfying constraints on the maximal loads exerted on the offshore support structure. The obtained results indicate that offshore high-altitude wind energy could bring forth significant advantages in terms of structural loads and, consequently, of offshore platform construction costs.

Keywords Innovative wind energy technologies, high-altitude wind energy, offshore wind energy

1 Introduction

The problem of sustainable energy generation is one of the most urgent challenges that mankind is facing today. On the one hand, the world energy consumption is projected to grow by 50% from 2005 to 2030, mainly due to the development of non-OECD (Organization for Economic Cooperation and Development) countries (see [1]). On the other hand, the problems related to the actual distribution of energy production among the different sources are evident and documented by many studies. Fossil fuels (i.e. oil, gas and coal) actually cover about 80% of the global primary energy demand (as reported in [1], updated to 2006) and they are supplied by few producer countries, which own limited reservoirs. The cost of energy obtained from fossil sources is continuously increasing due to increasing demand, related to the rapidly growing economies of the highly populated countries. Moreover, the negative effects of energy generation from fossil sources on global warming and climate change, due to excessive carbon dioxide emissions, and the negative impact of fossil energy on the environment are recognized worldwide and lead to additional indirect costs. One of the key points to solve these issues is the use of a suitable combination of alternative renewable energy sources. Focusing the attention on wind power, it can be noted that wind energy actually supplies about 0.3% of the global energy demand, with an average global growth of the installed capacity of about 27% in 2007 [2]. It is interesting to note that recent studies [3] showed that by exploiting 20% of the global land sites of class 3 or more (i.e. with average wind speed greater than 6.9 m/s at 80 m above the ground), the entire world's energy demand could be supplied. However, the installation of wind farms in many of such "good" inland sites is critical due to logistic problems, that give rise to higher costs, and/or due to possibly poor social acceptance for environmental (visual and acoustic) issues.

With the aim of solving such problems, offshore wind energy technology has been studied during the last 15 years as an alternative to inland wind turbines (see e.g. [4, 5]). The main advantage of offshore over inland wind turbines is the significantly higher offshore wind speed and, consequently, the higher generated power values. Moreover, the large space available for offshore turbine installation, without problems related to negative visual and acoustic impact, is another advantage of such a technology.

In this paper, an innovative concept of offshore wind energy is studied, in order to evaluate its potential to improve over the present offshore wind technology. In particular, the technology of high-altitude wind energy using controlled airfoils, is considered. The basic idea is to use tethered airfoils (e.g. power kites like the ones used for surfing or sailing), linked to the ground with cables which are employed to control their flight and to convert the aerodynamical forces into electrical power, using suitable rotating mechanisms and electric generators kept at ground level. The airfoils are able to exploit wind flows at higher altitudes than those of wind towers (up to 1000 m), where stronger and more constant wind can be found basically everywhere in the world (see [6]): thus, controlled airfoil technology can be used in a much larger number of locations. The potentials of such a technology for has been theoretically investigated almost 30 years ago [7], showing that if the airfoils are driven to fly in "crosswind" conditions, the resulting aerodynamical forces can generate surprisingly high power values. However, only in the past few years more intensive studies have been carried out by some research groups ([8, 9, 10, 11]), to deeply investigate this idea from the theoretical, technological and experimental point of views. In particular, at Politecnico di Torino, exploiting the recent advances in the modeling and control of complex systems, automated control strategies have been developed to drive the airfoil flight in crosswind conditions. Moreover, a small-scale prototype has been realized to experimentally verify the obtained theoretical and numerical results ([10, 11, 12, 13]).
In this work, the application of a high-altitude wind energy technology denoted as Kitenergy, developed in Italy by Politecnico di Torino and by the high-tech company Modelway S.r.l., is studied in the offshore context. In particular, theoretical and numerical studies are carried out in order to evaluate the loads exerted on the support structure by a 3-MW Kitenergy generator and its average yearly generated power. The obtained results are encouraging and indicate that offshore high-altitude wind energy could be an interesting technology to be employed in deep sea locations, where the actual wind technology would be not profitable due to excessive costs and critical technical issues.

2 High-altitude wind energy using controlled airfoils

2.1 Basic concepts

The key idea of the Kitenergy technology is to harvest high-altitude wind energy with the minimal effort in terms of generator structure, cost and land occupation. A high-altitude wind generator is composed by a light airfoil able to fly fast in crosswind conditions and connected to the ground by two cables. The latter are realized in composite materials, with a traction resistance 8-10 times higher than that of steel cables of the same weight. The

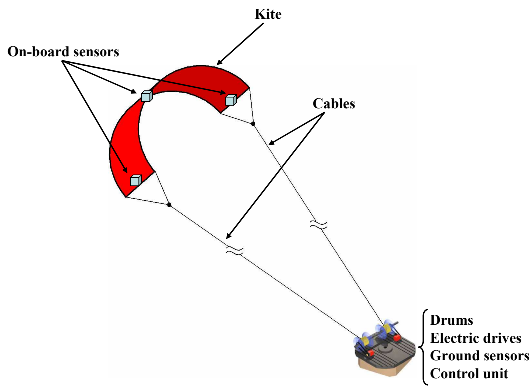

Figure 1: scheme of a Kite Steering Unit (KSU)

cables are rolled around two drums, linked to two electric drives which are able to act either as generators or as motors. An electronic control system can drive the kite flight by differentially pulling the cables (see Figure 1). The kite flight is tracked and controlled using on-board wireless instrumentation (GPS, magnetic and inertial sensors) as well as ground sensors, to measure the airfoil speed and position, the power output, the cable force and speed and the wind speed and direction. 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 Kitenergy technology. The KSU can be employed in different ways to generate energy: in this paper, the so-called KE-yoyo configuration (see [10, 12, 13]) is considered.
In a KE-yoyo generator, the KSU is fixed with respect to the ground and energy is obtained by continuously performing a two-phase cycle, depicted in Figure 2(a): in the *traction phase* the kite exploits wind power to unroll the lines and the electric drives act as generators, driven by the rotation of the drums. During the traction phase, the kite is controlled so to fly fast in crosswind direction, to generate the maximum amount of power. When the maximum line length is reached, the *recovery phase* begins and the kite is controlled in such a way that its aerodynamic lift force collapses: this way, the energy spent to rewind the cables is a fraction (less than 15%) of the amount generated in the traction phase. Numerical and theoretical analyses have been carried out to investigate the potentials of a KE-yoyo unit using the described operating cycle (see e.g. [10, 12]). The results of such studies are resumed in the next Section.

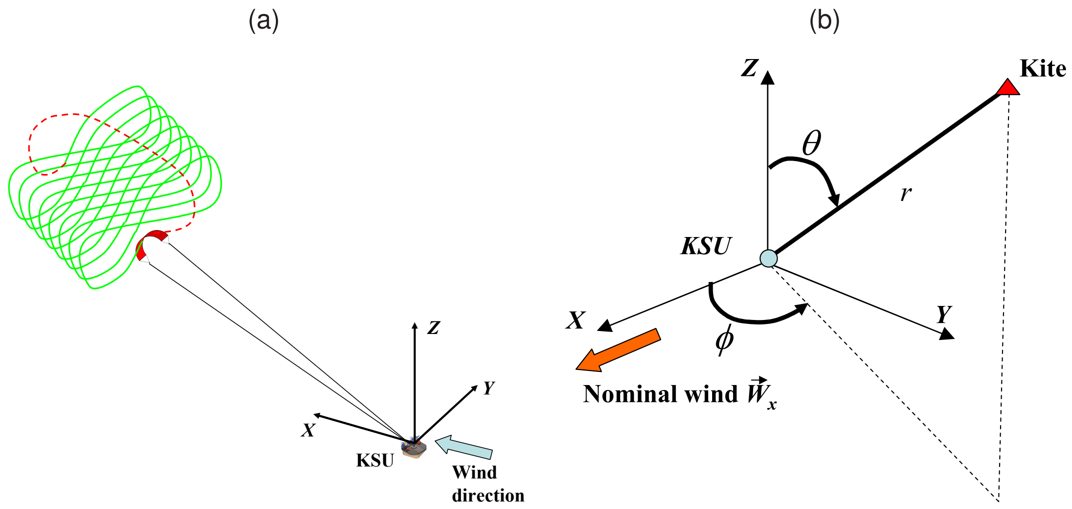

Figure 2: (a) KE-yoyo configuration cycle: traction (solid line) and passive (dashed line) phases. (b) Model diagram of a KE–yoyo.

2.2 Numerical analyses of a KE-yoyo generator

The KE-yoyo operational cycle has been developed and tested through numerical simulations, considering a quite accurate system model, which takes into account the aerodynamic characteristics of the kite and the cables. In such a model, the position of the airfoil is expressed in terms of spherical coordinates (θ, ϕ, r), as shown in Figure 2(b). In the numerical analyses, advanced control techniques have been employed to maximize the net generated energy. In particular, a Nonlinear Model Predictive Control (NMPC, see e.g. [14]) strategy has been employed. Such a control strategy allows to maximize the generated energy while explicitly taking into account the state and input constraints, related to actuator limitations and to the need of preventing the airfoil from falling to the ground and the lines from entangling. In order to implement the NMPC law in real time at the required sampling time (of the order of 0.2 s) a fast implementation technique of, denoted as FMPC (see [15]), is used. The employed control technique is able to stabilize the kite path while optimizing the generated energy, also in presence of quite strong wind disturbance [10, 12]. In the performed studies, a wind shear model (see e.g. [3]) has been also considered to describe the variation of nominal wind speed $W_x(Z)$ with respect to the altitude Z. Such a model has been identified using the data contained in the database RAOB (RAwinsonde OBservation) of the National Oceanographic and Atmospheric Administration, see [16]. An example of winter and summer wind shear profiles related to the site of Leba in Poland is reported in Figure 3.

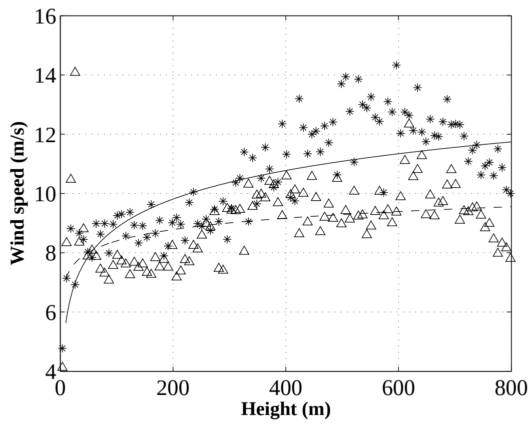

Figure 3: Wind shear model related to the site of Leba, in Poland, for winter months (model: solid line, measured data: asterisks) and for summer months (model: dashed line, measured data: triangles)

On the basis of the described numerical simulations, the power curve of a KE-yoyo with the characteristics reported in Table 1 has been computed (see Figure 4). Such a curve gives the generated power as a function of wind speed: it can be noted that a net power value of 2 MW is obtained by the KE-yoyo with 9-m/s wind speed. The power curve is saturated at the rated value of 2 MW, corresponding to the maximum that can be obtained with the employed electric equipment.

Numerical simulations have been also employed to investigate the dependance of the mean generated power on the kite area and efficiency, on the average cable length during the cycle. In the performed simulations, if not differently specified, a kite with the characteristics of Table 1 has been considered. Moreover, the cable diameter has been dimensioned in accordance with the traction force exerted by the kite, which varies with the differ-

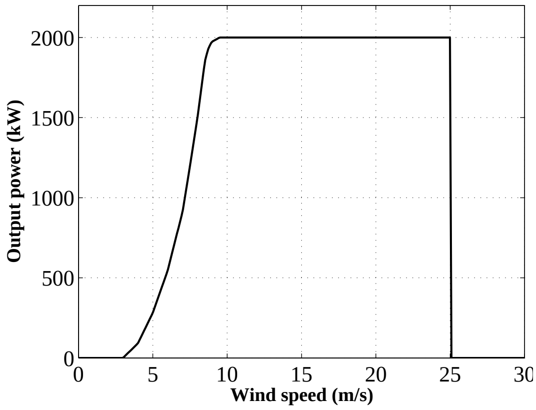

Figure 4: Power curve of a 2-MW KE-yoyo.

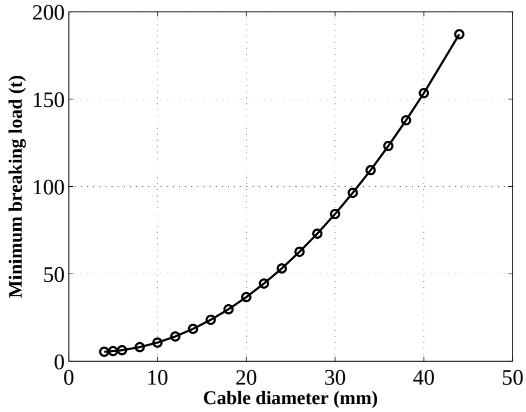

Figure 5: Dyneema cable breaking load characteristic as a function of diameter.

Table 1: KE-yoyo model parameters employed in the numerical simulations and in equation (1).

Kite mass (kg)	m	300
Characteristic area (m^2)	A	500
Base angle of attack (°)	α_0	3.5
Diameter of a single line (m)	d_l	0.04
Line density (kg/m^3)	ρ_l	970
Line drag coefficient	$C_{D,l}$	1.2
Minimum cable length (m)	$\underline{r}$	850
Maximum cable length (m)	$\overline{r}$	900
Air density (kg/m^3)	ρ	1.2
Average kite lift coefficient	$\overline{C}_L$	1.2
Average kite drag coefficient	$\overline{C}_D$	0.089
KE-yoyo cycle efficiency	η_c	0.7
Minimum breaking load of a single line (N)	$\overline{F}(d_l)$	$1.50\,10^6$
Maximum sway force (N)	$\overline{F}(d_l)$	$1.5\,10^6$
Minimal line speed (m/s)	$\dot{r}_{\min}$	-6.0
Maximal line speed (m/s)	$\dot{r}_{\max}$	6.0
Minimal elevation from the sea level (m)	$\underline{Z}$	30
Minimal angle θ (°)	$\underline{\theta}$	5
Safety coefficient	c_s	1.5
Airfoil wingspan (m)	w_s	80

ent considered parameter values. To this end, the breaking load characteristics of the polyethylene fiber composing the cables, reported in Figure 5, has been employed considering a safety coefficient equal to 2. The main results of the scalability studies are resumed in Figure 6(a)-(d). Basically, the generated power increases linearly with the kite area (Figure 6(a)) and according to a logistic-type function with the kite aerodynamic efficiency (Figure 6(b)). As regards the dependence on the average line length, it can be observed (Figure 6(c)) that there is an optimal point (which depends on the wind-elevation characteristic $W_x(Z)$) in which the positive effect of higher wind speed values, obtained with longer cables, is counter-balanced by the negative effect of higher cable weight and drag force. Beyond this point, an increase of cable length leads to lower mean generated power. Finally it can be noted that, as expected from aerodynamic laws, a cubic relationship exists between the generated power and the wind speed (Figure 6(d)). In particular, note that the same 500-m^2 kite can be used to obtain either a KE-yoyo with 2-MW rated power, reached at 9-m/s wind speed, or a KE-yoyo with 5-MW rated power, reached at about 12-m/s wind speed, without a significant cost increase except for the electric equipments. The power curve obtained through numerical simulations has been used, together with available wind speed data, to estimate the Capacity Factor (and, consequently, the average yearly generated power) of a Kitenergy generator, as it will be breifly shown in the next Section (for more details , the interested reader is referred to [10, 11]).

2.3 Capacity factor analysis

It is well known that, due to wind intermittency, the average power produced by a wind generator over the year is only a fraction, often indicated as "capacity factor" (CF), of the rated power. For a given wind generator on a specific site, the CF can be evaluated by knowing the probability density distribution function of wind speed and the generator wind-power curve. For example, Figure 7 shows, for the considered sites of Leba in Poland, the histograms of wind speed at 50-150 m over the ground, where the wind tower operates, and at 200-800 m over the ground, where the KE-yoyo can operate. Such estimates have been computed using the daily measurements of sounding stations collected over 11 years (between 1996 and 2006) and available on [16]. It can be noted that, in the elevation range 200-800 m, the average wind speed is 10 m/s and wind speeds higher than 12 m/s can be found with a probability of 33%. As a conse-

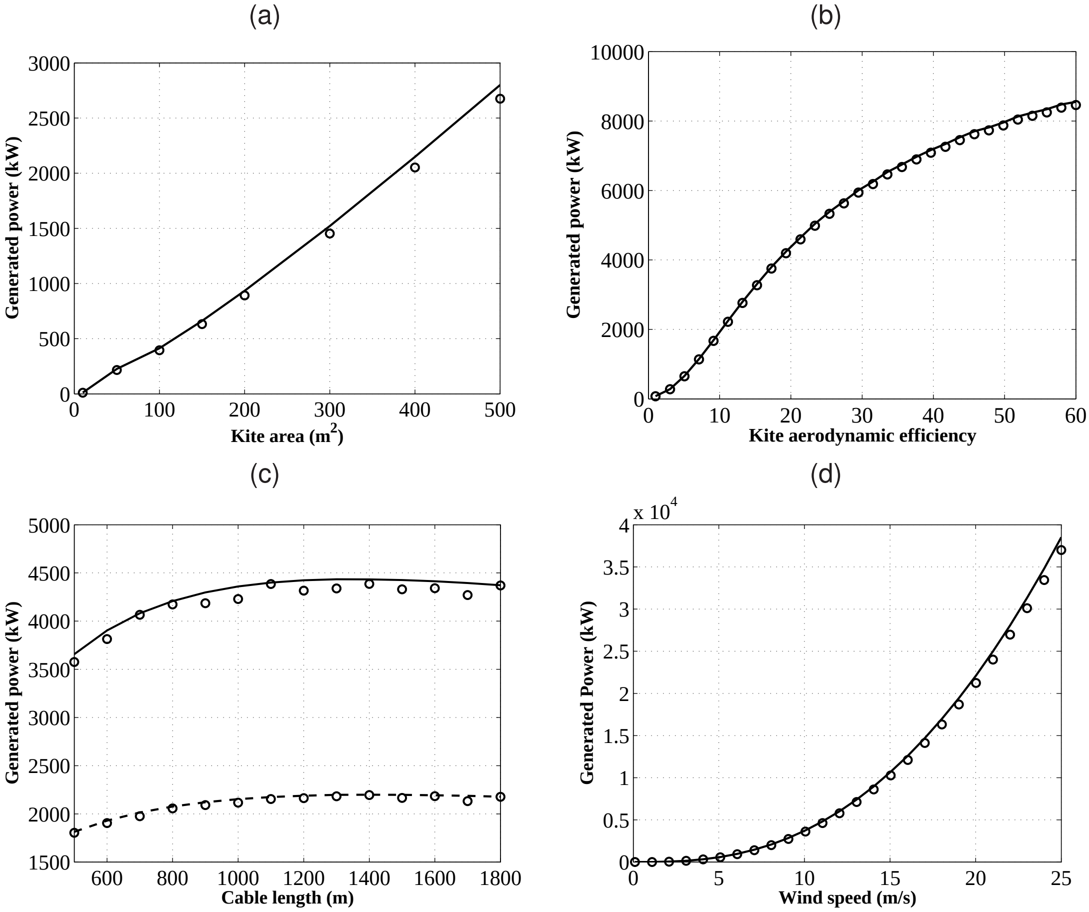

Figure 6: KE-yoyo, obtained net power as a function of: (a) airfoil area, (b) airfoil efficiency, (c) cable length for winter (solid) and summer (dashed) periods at Leba, (d) wind speed. Circles: numerical simulation results; solid lines: simplified equation results.

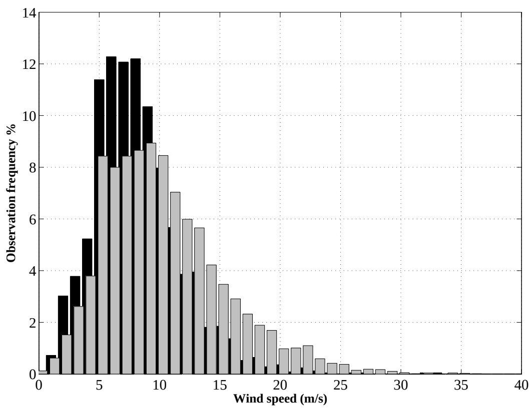

Figure 7: Wind speed measurements collected in Leba, Poland, at 50-150 m from the sea level (black) and at 200-800 m from the sea level (gray).

quence, the estimated CF value for a 2-MW KE-yoyo (whose power curve is reported in Figure 4) is equal to 0.68. Note that in the same site at 50-150 m above the ground, where a typical wind tower operates, the average wind speed is 8 m/s and wind speed values higher than 12 m/s occur only in the 15% of all the measurements. The corresponding estimated CF of a commercial 2-MW wind turbine is about 0.32.

2.4 Simplified power equations

The numerical tools described so far allow to simulate the operation of a KE-yoyo and to evaluate the capability of controlling the kite flight, maximizing the generated energy while preventing the kite from falling to the ground and the lines from entangling. Moreover, numerical simulations make it possible to evaluate the effects of wind turbulence on the system. However, simulation of the system takes a relatively large amount of time, due to computational complexity. Thus, simplified equations, giving the generated power and forces as a function of the wind speed and of the airfoil position, are useful to perform first-approximation studies of the performance of a KE-yoyo and to optimize its operational parameters, as it will be shown in Section 3 for the case of offshore Kitenergy application. The simplified equations of crosswind kite power (see e.g. [7, 12, 17]), are 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 airfoil speed relative to the ground is constant;
- the airfoil angle of attack is fixed.

Given these assumption, the average mechanical power $\overline{P}_{\text{KE-yoyo}}$ generated by a KE-yoyo unit during a cycle can be computed as:

$$\overline{P}_{\text{KE-yoyo}} = \eta_{\text{c}} C \left| W_x(\overline{Z}) \sin(\theta) \cos(\phi) - \dot{r}^{\text{trac}} \right|^2 \dot{r}^{\text{trac}} \quad (1)$$

where

$$\begin{aligned} \overline{Z} &= \cos(\theta)(\overline{r} + \underline{r})/2 \\ C &= \frac{1}{2} \rho A \overline{C}_L E_{\text{eq}}^2 \left(1 + \frac{1}{E_{\text{eq}}^2}\right)^{\frac{3}{2}} \\ E_{\text{eq}} &= \frac{\overline{C}_L}{C_{D,\text{eq}}} \\ C_{D,\text{eq}} &= \overline{C}_D \left(1 + \frac{(2\, r\, d_l)\, C_{D,l}}{4 A \overline{C}_D}\right) \end{aligned} \quad (2)$$

and $\eta_{\text{c}} \in (0,1)$ is a coefficient accounting for the losses of the energy generation cycle of a KE-yoyo. $\underline{r}$ and $\overline{r}$ are the minimum and maximum values of the cable length during a KE-yoyo cycle (i.e. at the beginning and at the end of each traction phase respectively), while $\overline{C}_L$ and $\overline{C}_D$ are the aerodynamic coefficients corresponding to the considered fixed angle of attack of the airfoil. Finally, $\dot{r}^{\text{trac}}$ 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:

$$F^{\text{c,trc}} = C \left| W_x(\overline{Z}) \sin(\theta) \cos(\phi) - \dot{r}^{\text{trac}} \right|^2 \quad (3)$$

The comparison between the results given by equations (1)-(3) and the numerical simulation results described in Section 2.2, reported in Figure 6(a)-(d), shows the good matching between the results given by these two tools.

2.5 Experimental results

At Politecnico di Torino, a small-scale KE-yoyo prototype has been built (now being tested in a marine environment, see Figure 8 and [18]), equipped with two Siemens® permanent-magnet synchronous motors/generators with 20-kW peak power and 10-kW rated power each. The energy produced is accumulated in a series of batteries that have a total voltage of about 340 V. The batteries also supply the energy to roll back the lines when needed. The prototype is capable of driving the flight of 5-20-m^2 kites with cables up to 1000 m long (see [12] for further details on the prototype). The objective of the first tests of the Kitenergy technology was to test the concept and to assess the matching between real-world data and numerical/theoretical results regarding the generated energy. Figure 9 shows the comparison between simulated and experimental data related to an experimental test performed near Torino, Italy. It can be noted that quite a good matching exists between the experimental and the numerical results, with wind turbulence (whose value at the kite's elevation could not be

Figure 8: KE-yoyo small scale prototype operating in Liguria, Italy, mounted on a boat.

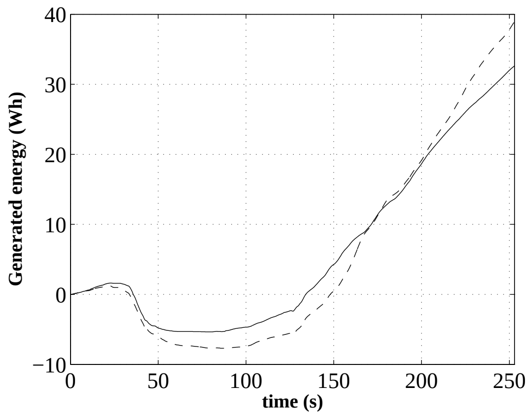

Figure 9: Comparison between the measured (dashed) and simulated (solid) generated energy obtained with a small-scale KE-yoyo generator. The experimental tests have been carried out (b) near Torino, Italy, in January 2008.

measured with the available test equipments) being the main source of error. The average numerical and measured power values are quite similar: mean measured power values of 441 W and 555 W have been obtained in the two tests, while the simulated average values are 400 W and 510 W respectively, i.e. an error of about 10% is observed. Such a good matching between the measured and simulated generated energy gives a good confidence level in the numerical and theoretical tools, which can be therefore employed to perform a realistic study of the energy generation potential of larger KE-yoyo generators.

3 Design and optimization of an offshore KE-yoyo generator

The problem of suitably designing the operational parameters of an offshore KE-yoyo generator placed in a given site is now considered, in order to maximize the generated power for given load constraints on the support structure. In particular, a fixed-bottom offshore generator will be considered, installed in a 20-m deep sea (see the sketches of Figure 10, that are only indicative and do not represent real proportions since, for example, the cable length in a KE-yoyo is between about 500 and 1000 meters).

The KE-yoyo operating parameters subject to optimization are the minimum cable length $\underline{r}$ during the operational cycle, the average inclination θ of the lines with respect to the vertical axis Z (see Figure 10) and the cable unrolling speed $\dot{r}$ during the traction phase. The cable length variation during the cycle Δr is fixed, thus the maximum cable length can be computed as $\overline{r} = \underline{r} + \Delta r$. According to the simplified equations of generated power (1)-(2), the following optimization problem can be considered to design the operational parameters of the KE-yoyo:

$$(\theta^*, \dot{r}^*, \underline{r}^*) = \arg\max \overline{P}_{\text{KE-yoyo}}(\theta, \dot{r}, \underline{r})$$

Furthermore, operational constraints have to be taken into account in the optimization, in order to find out feasible operating conditions and to avoid excessive loads on the support structure. In particular, the involved constraints regard the maximal and minimal cable unrolling/rewinding speed, the minimal elevation of the airfoil from the sea (considering also its maneuvering radius, the minimal angle θ during the cycle, the cable breaking force and the sway force F_S exerted on the support structure (see Figure 10). Indeed, analyses similar to those presented here can be easily carried out considering also other kind of loads (e.g. fatigue) and other kinds of installations (e.g. floating offshore). The constraints on the line speed are the following:

$$\dot{r}_{\text{min}} \leq \dot{r} \leq \min(W_x(\underline{r}\cos(\theta))\sin(\theta), \dot{r}_{\text{max}})$$

where $\dot{r}_{\text{min}}$, $\dot{r}_{\text{max}}$ are either imposed by the limitations of the electric drives employed on the KSU or chosen in order to prevent excessive cable wear due to the high unrolling/rewinding speed. A minimal elevation $\underline{Z}$ over the sea can be imposed by requiring that (see Figure 10):

$$\underline{r}\cos(\theta + \tfrac{5w_s}{2\underline{r}}) \geq \underline{Z}$$

where w_s is the airfoil wingspan. Indeed, the term $\frac{5w_s}{2\underline{r}}$ takes into account the variation of θ that may occur during the flight, due to the airfoil's minimal maneuvering radius. A technical constraint on the minimal value of θ is also introduced:

$$\theta - \frac{5w_s}{2\underline{r}} \geq \underline{\theta}$$

with $0 \leq \underline{\theta} \leq \pi/2$. The constraint related to the cable breaking load can be expressed, for two cables with a given cable diameter d_l, as:

$$F^{\text{c,trc}} \leq 2c_s\overline{F}(d_l)$$

where $\overline{F}(\cdot)$ is the minimum breaking force of a single cable (see Figure 5), c_s is a safety coefficient and $F^{\text{c,trc}}$ is the overall traction force exerted on the cables, computed according to equation (3). Finally, a constraint on the maximal sway force applied to the support structure can be imposed by considering the component of the cable traction force $F_S^{\text{c,trc}}$ parallel to the sea surface, when the kite inclination with respect to the vertical axis is maximum:

$$F^{\text{c,trc}}\sin(\theta + \tfrac{5w_s}{2\underline{r}}) = F_S^{\text{c,trc}} \leq c_s\overline{F}_S$$

where $\overline{F}_S$ is the maximal sway force that the support structure and foundations can bear and the safety coefficient c_s is assumed for simplicity (and without loss of generality) to be the same as the one considered for the maximal cable traction force. Note that the constraint on the maximal sway force $\overline{F}_S$ can be imposed in order either to achieve low structure costs on new installations or to avoid excessive solicitations on existing structures, e.g. dismissed oil and gas platforms.

Considering all the described constraints, the optimization problem to be solved is given by:

$$\begin{array}{c}
(\theta^*, \dot{r}^*, \underline{r}^*) = \arg\max \overline{P}_{\text{KE-yoyo}}(\theta, \dot{r}, \underline{r}) \\
\text{s. t.} \\
\dot{r}_{\text{min}} \leq \dot{r} \leq \min(W_x(\underline{r}\cos(\theta))\sin(\theta), \dot{r}_{\text{max}}) \\
\underline{r}\cos(\theta + \frac{5w_s}{2\underline{r}}) \geq \underline{Z} \\
\theta - \frac{5w_s}{2\underline{r}} \geq \underline{\theta} \\
F_{\text{trac}}^{\text{c,trc}} \leq 2c_s\overline{F}(d_l) \\
F_S^{\text{c,trc}} \leq c_s\overline{F}_S
\end{array} \quad (4)$$

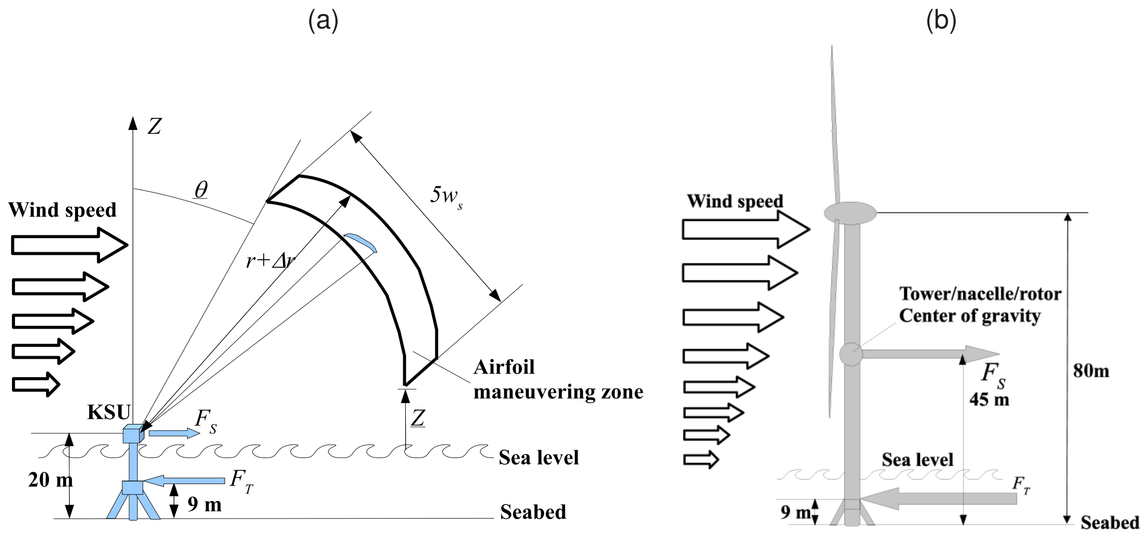

Figure 10: (a) Fixed-bottom offshore KE-yoyo operation: constraints on minimal elevation Z and on minimal angle θ and sway force F_s. (b) Fixed-bottom offshore wind tower. The sketches presented in this figure are only indicative and do not represent real proportions (since, for example, the cable length in a KE-yoyo is between about 500 and 1000 meters).

The solution of the optimization problem (4) has been calculated using the same system and constraints data given in Table 1 (except for $m = 480\,$kg and $A = 800\,$m^2) and considering the wind shear model related to the site of Leba, Poland (see Figure 3 in Section 2.2). The following results have been obtained:

$$\begin{pmatrix} \theta^* \\ \dot{r}^* \\ \underline{r}^* \end{pmatrix} = \begin{pmatrix} 70^\circ \\ 3.9\,\text{m/s} \\ 715\,\text{m} \end{pmatrix} \tag{5}$$

The corresponding average generated power is 2.7 MW and the average wind speed at the mean airfoil height (i.e. 234 m above the sea) is equal to 9.5 m/s. It has to be noted that the constraint on the sway force is active, thus limiting the generated power in order to satisfy the imposed maximal sway of $1.5\,10^6\,$N. The optimal operating parameters without considering the sway force limit are $\theta^* = 60^\circ$, $\dot{r}^* = 2.99\,$m/s, $\underline{r}^* = 676\,$m with a generated power of 2.9 MW, limited by the cable breaking load constraint. Therefore, it can be noted that by changing the kite position and the line unrolling speed, the forces on the support structure can be limited. The resulting range of degrees of freedom, that allows one to adapt the system to wind conditions, is one of the major advantages of Kitenergy technology.

Thus, with the optimized parameters (5), an offshore KE-yoyo with 3 MW rated power achievable at a nominal wind speed of about 10 m/s could be designed, with a maximal sway force of $1.5\,10^6$N. Interesting considerations can be drawn regarding the amount of sway load exerted on the support structure. Considering the maximal sway force of $1.5\,10^6\,$N exerted by the lines of the designed 3-MW KE-yoyo, and supposing that such a force is exerted at 20 m from the seabed (see Figure 10), the resulting force F_T that has to be opposed by the sea fastening system (supposed to be at 9 m form the seabed, see [19]) can be computed as:

$$F_{T,\text{HG}} = \frac{20}{9}\,1.5\,10^6 = 3.3\,10^6\,\text{N}$$

To have a term of comparison, in the case of a 3-MW-rated-power, 80-m-high wind turbine, according to [19] a sway force of about $2\,10^6\,$N is exerted at the center of gravity of the overall structure (i.e. the tower plus the nacelle and the rotor), which is placed at about 45 m above the seabed. The resulting force F_T that has to be opposed by the sea fastening system is:

$$F_{T,\text{Tower}} = \frac{45}{9}\,2\,10^6 = 1\,10^7\,\text{N}$$

Thus, we can conclude that the extreme statical load on the support structure due to sway force in the case of Kitenergy technology is about three times lower than that of a wind turbine of the same rated power.

To properly analyze the load in the case of the proposed high-altitude wind energy generator, the dynamical behavior of the structure should be also considered. In particular, the support structure has to be designed so that the first natural frequency is different from the frequencies of the excitations induced by the waves [20], which are typically up to $0,4Hz$ in open sea.An approximation of the first natural frequency f_{nat} for an offshore wind support structure is computed in [20], were $f_{\text{nat}} \approx L^{-2}$, being L the structure height. Thus, considering that

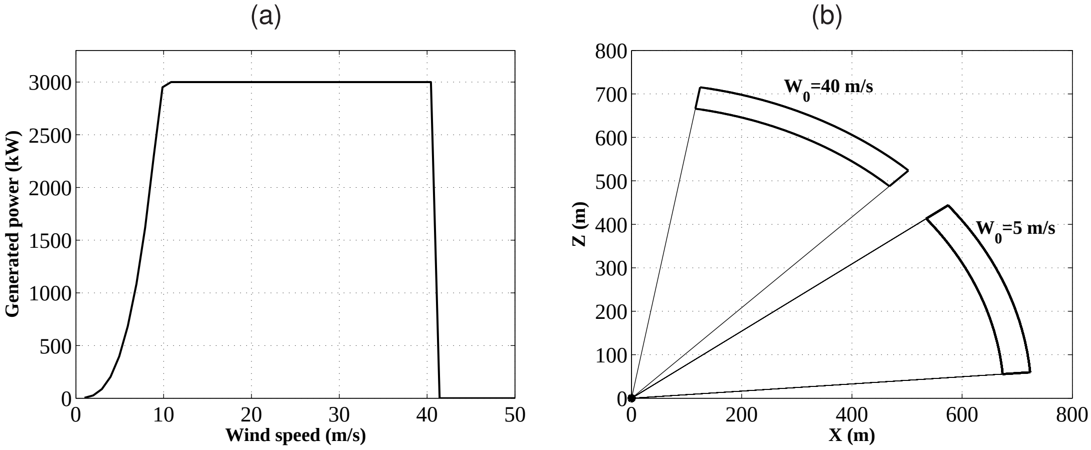

Figure 11: (a) Power curve of an offshore 3-MW KE-yoyo generator. (b) Variation of the airfoil operating zone with different wind speed values.

the first natural frequency of a typical 3-MW, 80-m-high wind tower is about 0.25 Hz, in a first approximation the first natural frequency of the structure of an offshore 3-MW KE-yoyo (which is approximately 4 times shorter than a wind tower, see Figure 10) is about 4 Hz. This value is about 16 times higher than that of a wind tower and about 10 times higher than the bandwidth of wave excitations, with consequent structural and economical advantages. Once the nominal operating conditions of the offshore KE-yoyo generator have been designed, an optimization procedure similar to the one illustrated so far can be used to compute the optimal operating parameters with different wind speed values, thus computing the generator power curve. the obtained results are shown in Figure 11(a). It can be noted that a quite high cut-out wind speed (about 40 m/s) is achieved, thus maximizing the range of wind speed values in which energy can be produced. This result can be obtained obtained thanks to the capability of making the airfoil fly with lower θ angles (see figure 11(b)), where the traction force exerted on the cables is lower as it can be noted in equation (3).

4 Conclusions

The paper described the offshore application of an innovative high-altitude wind energy technology, denoted as Kitenergy. In previous works [11] it has been shown, through theoretical and numerical studies partially confirmed by preliminary experiments, that this technology is interesting for its relatively high generated power per unit area and its potential applicability in a wide number of sites, including also those with little or no wind below 200 m above the ground. In the offshore context, the preliminary results presented in this work indicate that Kitenergy technology could bring forth interesting advantages also in terms of structural loads and, consequently, platform construction and installation costs. Indeed, more accurate analyses have to be carried out, considering also the maintenance and operations costs, however the obtained results are encouraging and indicate that Kitenergy technology could be profitably employed also in deep sea locations.

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