High-altitude wind energy for sustainable marine transportation

Lorenzo Fagiano, *Member, IEEE,* Mario Milanese, *Senior Member, IEEE,* Valentino Razza, and Mario Bonansone
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***Abstract*—This paper investigates the use of a controlled tethered wing, or kite, for naval transportation. Linked to a boat by light composite-fibre lines, the kite is able to fly between 200 m and 600 m above the sea and to generate high traction forces. A mechatronic system installed on the boat, named Kite Steering Unit (KSU), controls the kite and converts the line speed and force into electricity. Differently from previous works, the boat is also equipped with electric propellers, so that naval propulsion can be achieved both directly, through the towing forces exerted by the lines, and indirectly, through the electricity generated by the KSU and fed to the electric propellers via a battery pack. The optimal system operating conditions, that maximize the boat speed for given wind characteristics, are computed. Then, a model predictive controller is designed and numerical simulations with a realistic model are carried out, in order to assess the performance of the control system against the optimal operating conditions. The results indicate that, with this system, a completely green naval transportation system can be obtained, regardless of the wind direction.**

***Index Terms*—Marine transportation, Wind energy, Control systems, Optimal control**

I. Introduction

In the last decade, several research and development activities have been carried out, regarding novel wind power technologies that aim to convert high-altitude wind energy (HAWE) into electricity, by exploiting the flight of controlled tethered wings or kites (see e.g. [1], [2], [3], [4]). These kites can fly at high speed in "crosswind" conditions, i.e. in a direction that is roughly perpendicular to the wind, thus generating high traction forces on the lines, as introduced in the seminal work of [5]. Such forces are then converted into mechanical and electrical energy by a suitable mechatronic system placed on the ground (see e.g. [6], [7], [8]). The studies that have been carried out so far, including theoretical and numerical analyses as well as experiments with small-scale prototypes, indicate that this kind of technology, named Kitenergy in this paper, could produce electricity at lower cost than fossil fuels, [6]. This result can be achieved mainly thanks to much lower costs for the generator construction, higher capacity factor, and lower land occupation with respect to the actual wind power technology, based on wind turbines.

L. Fagiano is with Dip. di Automatica e Informatica, Politecnico di Torino, Italy, and with the Dept. of Mechanical Engineering, University of California at Santa Barbara, USA. E-mail: lorenzo.fagiano@polito.it, lorenzo.fagiano@engineering.ucsb.edu.

M. Milanese is with Kitenergy S.r.l., Torino, Italy. E-mail: mario.milanese@kitenergy.net.

V. Razza is with the Dip. di Automatica e Informatica, Politecnico di Torino, Torino, Italy. E-mail: valentino.razza@polito.it

M. Bonansone is with Modelway S.r.l., Torino, Italy. E-mail: mario.bonansone@modelway.it.

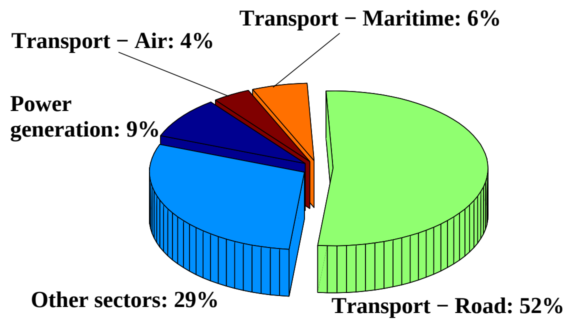

Fig. 1. Distribution, among different uses, of the total CO_2 emissions in 2006 related to oil consumption. The total global emissions of carbon dioxide were 28 Gt, of which 38% related to oil use (Source: [9]).

Another interesting application of controlled kites is naval transportation, which accounted for about 6% of the global carbon-dioxide emissions from oil use in 2006, i.e. 2% more than the emissions caused by air-transportation (see Fig. 1). Also in this field, research activities have been recently carried out, mainly to study the control design for power kites used to tow a boat (see [10], [11]). Moreover, a system for naval propulsion using power kites has been also industrialized (see [12]). In all these cases, the kite is used to directly tow a boat, like a classical sail does, so that the useful effect of propelling the boat can be obtained only with limited wind conditions: roughly speaking, the kite is able to pull the boat if the angle between the wind and the boat speed vector ranges from 0° (i.e. the boat moves downwind) to approximately 135° (i.e. 45° against the wind). The idea of this paper is to remove such a limit by using a Kitenergy system, able to convert wind energy into electricity onboard, together with electric propellers placed on the boat, so that the boat propulsion can be obtained from the wind not only directly, through the towing forces exerted by the kite's lines, but also indirectly, thanks to the action of the propellers. Electricity is supplied to the propellers by a battery pack, and the batteries are recharged with the electric energy generated by the Kitenergy generator itself. The aim of this paper is to investigate the potentials and the control aspects of this new kind of "hybrid kite boat", which represents a novelty with respect to the existing studies and applications. Indeed, the combined use of kite traction and electric propellers opens up new possibilities, like the already mentioned capability of navigating upwind using the electric propellers, and also new conceptual issues, regarding the computation of an optimal tradeoff between the use of kite towing and of electric propulsion, for given wind direction relative to the boat, to achieve the maximal boat

Fig. 2. KE-yoyo prototype installed on a boat and operating near Genoa, Italy.

speed. Moreover, the system operating conditions have to be chosen in order to ensure their sustainability, in the sense that the state of charge of the batteries on the boat must be kept sufficiently high, so to avoid voltage losses, while providing the required power for the electric propellers and for the onboard auxiliaries like lights, pumps, etc.. Finally, for safety reasons the kite must fly sufficiently far from the sea and the line forces have to be contained, so to avoid line breaking and excessive roll moments on the boat. In this work, it will be shown how the described problem can be formulated, by using a simplified system model, as a constrained numerical optimization problem, in which the boat speed is maximized subject to constraints on the average generated electric energy, on the kite position and on the line forces. Then, the devised optimal operating conditions provide guidelines on how to design some of the system parameters, as well as on how to design a feedback controller, based on a Nonlinear Model Predictive Control (NMPC, see e.g. [13]) strategy. The latter is employed to carry out numerical simulations with a realistic dynamical model of the system, in order to assess the feasibility of the computed optimal operating conditions and to evaluate the system's performance also in the presence of external disturbances, like wind turbulence. To the best of the authors' knowledge, there is no existing study in the literature concerned with the optimization and control of the described hybrid kite boat. The results of this paper show that the concept is viable, moreover the proposed optimization approach represents a general tool that can be used to analyze and carry out a first-approximation design of this kind of transportation systems. The paper is organized as follows. Section II describes that layout of the considered system. Modeling is treated in Section III, while the hybrid kite boat optimization and control design are described in Sections IV and V-A, respectively. Section V-B is concerned with the numerical simulations of the system, while conclusions are given in Section VI.

II. System layout

In the considered application of high-altitude wind power to naval propulsion, a so-called KE-yoyo generator is installed on a boat. A prototype of this system has been built at Politecnico di Torino, in cooperation with the yacht manufacturer Azimut-Benetti and the high-tech company Modelway (see Fig. 2 and the movie [14]). In a KE-yoyo, the kite is connected to the boat by two lines, realized in composite materials, with a traction resistance 8-10 times higher than that of steel lines of the same weight. On the boat deck, the lines are rolled around two drums, linked to two reversible electric motors, commanded by drives which are able to act also as generators. The kite can be controlled by differentially pulling the lines with the electric motors and it is tracked using onboard wireless instrumentation (GPS, magnetic and inertial sensors) that allow to measure the wing speed and position. Other sensors, installed on the boat, measure the generated current i_{KSU}, the line force $F^{\text{t,trc}}$, length r, and speed $\dot{r}$, and the wind speed and direction. Although not present in the described prototype, a laser imaging system like the one used in [15] might also be employed to track the kite motion. The system composed by the electric motors and drives, the drums, and all the hardware needed to control a single kite is denoted as Kite Steering Unit (KSU). In a KE-yoyo, electric energy is generated by continuously repeating a two-phase cycle, depicted in Fig. 3: in the *traction phase* the kite is controlled so to fly fast in crosswind direction, and the lines are unrolled at a reference speed $\dot{r}_{\text{ref}}^{\text{trac}} > 0$, under the pull of high traction forces, thus generating energy through the electric generators. When the maximal line length is reached, the *passive phase* begins and the kite is controlled, by modifying its angle of attack, so that the traction forces collapse: in this way, the lines can be rolled back at a reference speed $\dot{r}_{\text{ref}}^{\text{pass}} < 0$, spending less than 10% of the energy collected in the previous phase (see [7], [8] for details on the KE-yoyo cycle). The energy produced is stored in a battery pack on the boat. The batteries supply a current i^{aux} to the boat auxiliary equipments (e.g. lights, pumps, etc.) and a current i^{motor} to the electric propellers, which can be used to generate a force F^{motor} to propel the boat. A conceptual scheme of the described system is shown in Fig. 4.

III. System Model

As anticipated in the Introduction, a detailed, dynamical model of the system is employed for control design and numerical simulations, while a simplified model is used to optimize the system operating conditions.

A. Detailed model

Wind and boat models. A Cartesian coordinate system (X, Y, Z) is considered (see Fig. 5), centered at the boat location (i.e. at the KSU, which is fixed with respect to the boat), with X axis aligned with the longitudinal symmetry axis of the boat. Wind speed vector is denoted as $\vec{W}_l = \vec{W}_0(t) + \vec{W}_t(t)$, where t is the continuous time variable and $\vec{W}_0(t)$ is the nominal wind, supposed to be measured and expressed in (X, Y, Z) as:

$$\vec{W}_0(t) = \begin{pmatrix} W_n(Z)\cos(\Theta(t)) \\ -W_n(Z)\sin(\Theta(t)) \\ 0 \end{pmatrix} \tag{1}$$

$\Theta(t)$ is the angle between the nominal wind speed direction and X axis, while $W_n(Z)$ is a known function which gives the nominal wind magnitude at the altitude Z. In this paper, function $W_n(Z)$ corresponds to a power-law wind shear model (see e.g. [16]):

$$W_n(Z) = \overline{W}\left(\frac{Z}{\overline{Z}}\right)^{\beta}, \tag{2}$$

where the values of $\overline{W}$, $\overline{Z}$ and β have been identified using the data contained in the database RAOB (RAwinsonde OBservation) of the National Oceanographic and Atmospheric Administration, see [17]. The term $\vec{W}_t(t)$ may have components in all directions and it is not supposed to be known, accounting for unmeasured wind turbulence.

As regards the boat model, the following assumptions are considered:

- the boat rudder is commanded in such a way that the boat speed vector $\vec{v}(t)$ is aligned with axis X;
- the boat moves along a straight path;
- the boat longitudinal acceleration $\dot{v}(t)$ is low as compared to the kite accelerations during the flight;
- the effects of the lateral forces exerted by the lines on the boat direction are negligible and/or balanced by a suitable action on the rudder and by a differential action of the electric propellers;

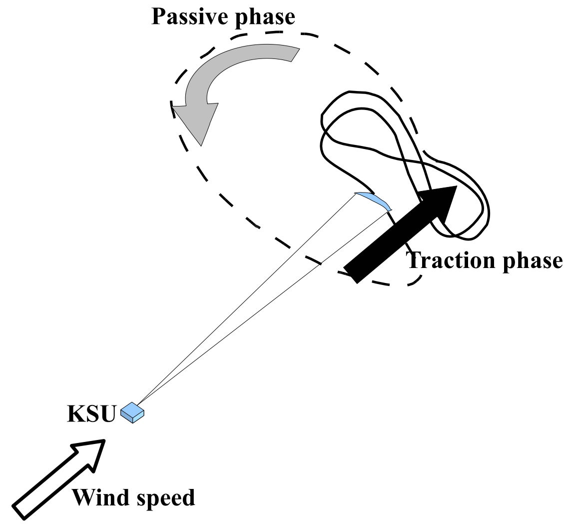

Fig. 3. Sketch of a KE-yoyo cycle: traction (solid) and passive (dashed) phases.

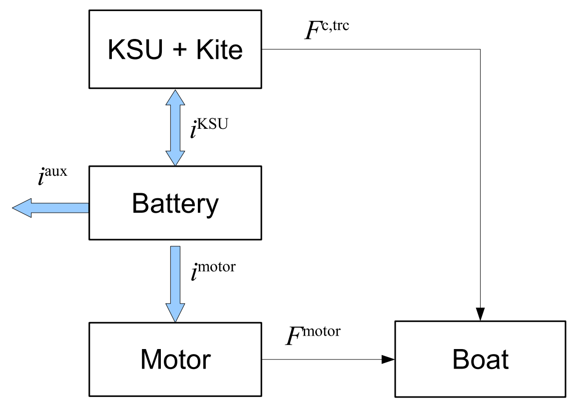

Fig. 4. Conceptual scheme of the hybrid kite boat.

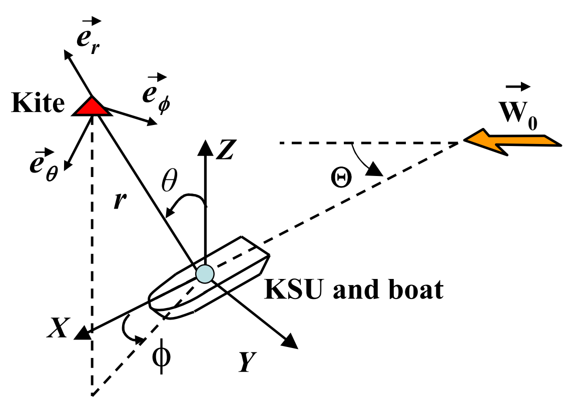

Fig. 5. Model diagram of the system.

According to such assumptions, the angular speed of the boat is zero or negligible. The considered assumptions are reasonable in the context of this paper and allow to describe with satisfactory accuracy the longitudinal motion of the boat pulled by the kite lines and/or under the action of the propellers. Since the speed vector $\vec{v}(t)$ is supposed to be aligned with axis X, its direction with respect to the nominal wind speed direction is univocally defined by angle $\Theta(t)$. Thus, in the following the boat speed will be described simply by its magnitude $v(t)$. Note that the speed vector is measured by using a GPS on the boat. On the basis of the considered assumptions, the model that describes the boat motion is given by the following equation:

$$\dot{v}(t) = \frac{F^{\text{tow}}(t) + F^{\text{motor}}(t) - F^{\text{R}}(v(t))}{M} \tag{3}$$

where M is the boat mass, $F^{\text{tow}}(t)$ is the towing force exerted by the kite lines and $F^{\text{R}}(v(t))$ is the longitudinal drag force acting on the boat at a given speed $v(t)$. Function $F^{\text{R}}(v)$, shown in Fig. 6, has been identified through experimental tests with the boat employed in the KiteNav project: it can be clearly noted that, at approximately 5 m/s speed, the boat motion regime changes from displacement to planning. The

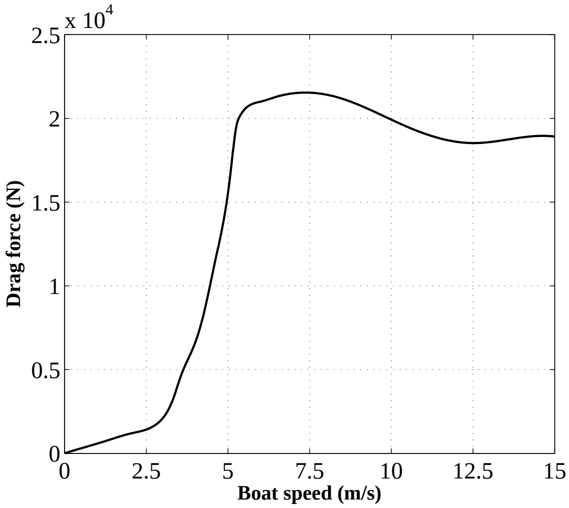

Fig. 6. Boat drag force $F^{\text{R}}(v)$

propellers' force $F^{\text{motor}}(t)$ can be computed according to the following formula:

$$F_{\text{motor}}(t) = \frac{\eta_{\text{motor}} V^{\text{battery}} i^{\text{motor}}(t)}{v(t)} \tag{4}$$

where V^{battery} is the battery voltage and η_{motor} is the overall efficiency of the electrical propellers. A reasonable value for η_{motor} is 0.54. For the purpose of this paper, the propellers' current $i^{\text{motor}}(t)$ is assumed to be always positive (i.e. the propellers can only draw current to push the boat forward) and it is regulated by a low-level controller in order to achieve an imposed value of the boat speed, indicated as v_{boat}.

Kite model. The kite model is thoroughly presented in [7], [8], and only a concise description is given here, for the sake of completeness. In system (X, Y, Z), the kite position can be expressed as a function of its distance $r(t)$ from the origin, which also corresponds to the lines' length, and of the two angles $\theta(t)$ and $\phi(t)$ as depicted in Fig. 5, where the three unit vectors $e_\theta(t)$, $e_\phi(t)$ and $e_r(t)$ of a local coordinate system, centered at the kite center of gravity, are also shown. Unit vectors $(e_\theta(t), e_\phi(t), e_r(t))$ are expressed in the Cartesian system (X, Y, Z) by:

$$\begin{pmatrix} e_\theta(t) & e_\phi(t) & e_r(t) \end{pmatrix} = \begin{pmatrix} \cos(\theta(t))\cos(\phi(t)) & -\sin(\phi(t)) & \sin(\theta(t))\cos(\phi(t)) \\ \cos(\theta(t))\sin(\phi(t)) & \cos(\phi(t)) & \sin(\theta(t))\sin(\phi(t)) \\ -\sin(\theta(t)) & 0 & \cos(\theta(t)) \end{pmatrix} \tag{5}$$

By applying Newton's laws of motion in the system $(e_\theta(t), e_\phi(t), e_r(t))$, the following dynamic equations are obtained:

$$\begin{aligned} \ddot{\theta}(t) &= \frac{F_\theta(t)}{m\, r(t)} \\ \ddot{\phi}(t) &= \frac{F_\phi(t)}{m\, r(t) \sin\theta(t)} \\ \ddot{r}(t) &= \frac{F_r(t)}{m} \end{aligned} \tag{6}$$

where m is the kite mass. Forces $F_\theta(t)$, $F_\phi(t)$ and $F_r(t)$ include the contributions of gravity force $\vec{F}^{\text{grav}}(t)$ of the kite and the lines, apparent force $\vec{F}^{\text{app}}(t)$, kite aerodynamic force $\vec{F}^{\text{aer}}(t)$, aerodynamic drag force $\vec{F}^{\text{c,aer}}(t)$ of the lines and traction force $F^{\text{c,trc}}(t)$ exerted by the lines on the kite. Gravity forces take into account the kite weight and the contribution given by the weight of the lines. Apparent forces include centrifugal and inertial forces due to the kite movement only, since little acceleration $\dot{v}(t)$ of the boat is assumed. The kite aerodynamic force $\vec{F}^{\text{aer}}(t)$ can be derived via the computation of the lift and drag forces, $\vec{F}_L(t)$ and $\vec{F}_D(t)$ respectively, that depend on the wind speed at the kite altitude, on the air density ρ, on the kite speed with respect to the sea, on the kite area A, on the kite aerodynamic lift and drag coefficients, $C_L(t)$ and $C_D(t)$, which in turn depend on the kite angle of attack $\alpha(t)$ (see [7] for more details), finally on the command angle $\psi(t)$, i.e. the control variable. The latter is defined as

$$\psi(t) \doteq \arcsin\left(\frac{\Delta l(t)}{d}\right) \tag{7}$$

with d being the distance between the two lines fixing points at the kite and $\Delta l(t)$ the length difference of the two lines

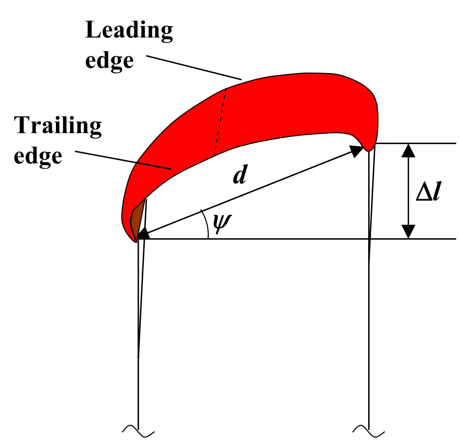

Fig. 7. Scheme of the control input $\psi(t)$.

(see Fig. 7), which can be issued by a suitable control of the electric motors. Finally, the influence of the lines is taken into account in the model through their drag force $\vec{F}^{\text{c,aer}}(t)$ and the traction force $F^{\text{c,trc}}(t)$. $\vec{F}^{\text{c,aer}}(t)$ depends on the line drag coefficient $C_{D,l}$, on the line length $r(t)$ and diameter d_l. The traction force $F^{\text{c,trc}}(t)$ is always directed along the local unit vector e_r and cannot be negative, since the kite can only pull the lines. Moreover, $F^{\text{c,trc}}(t)$ is measured by a force transducer on the KSU and, by using a low-level controller of the electric drives, it is regulated in such a way that $\dot{r}(t) = \dot{r}_{\text{ref}}$ where $\dot{r}_{\text{ref}}$ is a reference line rolling speed. The force $F^{\text{tow}}(t)$, exerted by the lines in the direction of the boat longitudinal motion, is given by the projection of $F^{\text{c,trc}}(t)$ on the X axis:

$$F^{\text{tow}}(t) = F^{\text{c,trc}}(t)\sin(\theta(t))\cos(\phi(t)) \tag{8}$$

The electric current $i^{\text{KSU}}(t)$ produced or consumed by the KSU is computed as:

$$i^{\text{KSU}}(t) = \frac{\eta_{\text{KSU}} F^{\text{c,trc}}(t)\dot{r}(t)}{V^{\text{battery}}}, \tag{9}$$

where η_{KSU} accounts for the mechanical and electrical efficiency of the KSU. A typical value is $\eta_{\text{KSU}} \simeq 0.95$.

Battery model. A simple current integrator is sufficient as battery model for the purpose of this work:

$$\dot{Q}(t) = \frac{i^{\text{KSU}}(t) - i^{\text{aux}}(t) - i^{\text{motor}}(t)}{C^{\text{battery}}}, \tag{10}$$

where $Q(t)$ is the state of charge of the batteries and C^{battery} is their capacity. The currents $i^{\text{aux}}(t)$ and $i^{\text{motor}}(t)$ are always positive, since the auxiliaries and the propellers can only draw current from the batteries, while $i^{\text{KSU}}(t)$, according to (9), may be either positive, when the KSU produces electricity, or negative, during the passive phase of the KE-yoyo cycle. Effects related to voltage variations due to low $Q(t)$ values, temperature and current rate are not taken in account, since they are not critical for the considered problem. The supply voltage V^{battery} is assumed to be constant.

Overall model equations. Considering that the nominal wind speed magnitude $W_n(Z(t))$ can be obtained by computing the kite altitude $Z(t)$ as $Z(t) = r(t)\cos(\theta(t))$, equations (1)–(10) give the system dynamics in the form:

$$\dot{x}(t) = f(x(t), u(t), \Theta(t), \vec{W}_t(t), i_{\text{aux}}(t), \dot{r}_{\text{ref}}, v_{\text{boat}}) \tag{11}$$

where $x(t) = [\theta(t)\ \phi(t)\ r(t)\ \dot{\theta}(t)\ \dot{\phi}(t)\ \dot{r}(t)\ v(t)\ Q(t)]^T$ are the model states and $u(t) = \psi(t)$ is the control input. All of the model states are measured using the available sensors installed on the kite and on the KSU. The model $f(\cdot)$ can be employed to design a control law for the kite and to simulate the system behavior.

B. Simplified model

The model presented in this Section stems from the simplified equations of a kite flying in crosswind conditions (see e.g. [8] and the references therein), which have been extended in this work in order to take into account the boat motion and the KE-yoyo generating cycle. The aim of this model is to provide, with simple equations, an estimate of the traction force acting on the lines and of the current generated by the KE-yoyo, for given system characteristics and operating conditions. The latter include the average values $\overline{\theta}$, $\overline{\phi}$ and $\overline{r}$ of θ, ϕ and r, respectively, during the KE-yoyo traction phase, the value $\dot{r}_{\text{ref}}^{\text{trac}}$ of the reference unrolling speed of the lines during the traction phase, and the boat speed v_{boat}. By assuming that:

- the kite flies fast 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 control angle ψ is small (i.e. $|\psi| \leq 10°$);

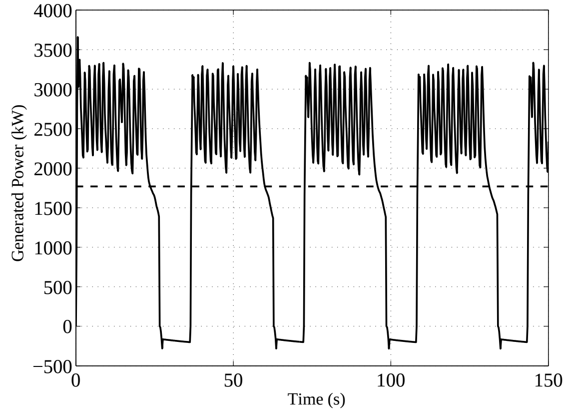

Fig. 8. Simulation of KE-yoyo cycles: course of the generated power.

it can be shown (see [8] for details) that, for given system characteristics and for a given fixed angle Θ, a simplified formulation of the pulling force acting on the lines during the traction phase of the KE-yoyo (see Section II) is:

$$\overline{F}^{\text{c,trc}}(\overline{\theta}, \overline{\phi}, \overline{r}, \dot{r}_{\text{ref}}^{\text{trac}}, v_{\text{boat}}) = \frac{1}{2}\rho A C_L E_{\text{eq}}^2 \left(1 + \frac{1}{E_{\text{eq}}^2}\right)^{\frac{3}{2}} \vec{W}_{e,r}^2 \tag{12}$$

where

$$E_{\text{eq}} = \frac{C_L}{C_D\left(1 + \frac{(2\overline{r} d_l) C_{D,l}}{4 A C_D}\right)}, \tag{13}$$

and

$$\vec{W}_{e,r} = \left[W_n(\overline{r}\cos\overline{\theta})\cos\left(\Theta + \overline{\phi}\right) - v_{\text{boat}}\cos\overline{\phi}\right]\sin\overline{\theta} - \dot{r}_{\text{ref}}^{\text{trac}}. \tag{14}$$

In order to take into account the energy that is spent during the passive phase of the KE-yoyo cycle, in the simplified model an average generated power value, indicated by $\overline{P}^{\text{KE-yoyo}}$, is considered, computed as:

$$\overline{P}^{\text{KE-yoyo}} = \eta_{\text{KE-yoyo}}\eta_{\text{KSU}}\overline{F}^{\text{c,trc}}\dot{r} \tag{15}$$

where $\eta_{\text{KE-yoyo}} < 1$ is a coefficient that takes into account the efficiency of the KE-yoyo generator cycle, i.e. the ratio between the average generated power and the power generated in the traction phase only. Numerical analyses and the tests performed with a KE-yoyo prototype at the Politecnico di Torino (see, as an example, Fig. 8) show that $\eta_{\text{KE-yoyo}} \simeq 0.7$. Then, the average generated electrical current value $\overline{i}^{\text{KE-yoyo}}$ can be computed as:

$$\overline{i}^{\text{KE-yoyo}} = \frac{\overline{P}^{\text{KE-yoyo}}}{V^{\text{battery}}} \tag{16}$$

IV. Optimization of a hybrid kite boat

The optimization problem and related objectives are now described. As highlighted in Section I, the aim is to compute, for given wind speed and angle Θ, the operating conditions that maximize the boat speed, while feeding the boat auxiliaries with the required power and satisfying other operational constraints. The variables to be optimized are $\overline{\theta}$ and $\overline{\phi}$, which roughly give the wing position with respect to the boat, the reference line speed during the KE-yoyo traction phase, $\dot{r}_{\text{ref}}^{\text{trac}}$, and during the passive phase, $\dot{r}_{\text{ref}}^{\text{pass}}$, and the boat speed, v_{boat}. The average line length $\overline{r}$ is fixed a priori, as well as the total line length variation during a cycle, Δr, to reasonable values that have been used also in experiments on the boat prototype (see [14]). In particular, these values are $\overline{r} = 200\,\text{m}$ and $\Delta r = 50\,\text{m}$. The constraints to be taken into account are the following:

a) an upper limit $\theta^{\max}$ is imposed on the angle $\overline{\theta}$, to prevent the kite from getting too close to the sea;
b) in order to find an operating condition which is meaningful from a physical point of view, the projection of the effective wind speed vector along the line direction, $\vec{W}_{e,r}$ (14), has to be positive;
c) the magnitude of the reference line speeds, $\dot{r}_{\text{ref}}^{\text{trac}}$ and $\dot{r}_{\text{ref}}^{\text{pass}}$, is limited by a value $\bar{\dot{r}}$, to avoid excessive line wear;
d) an upper limit on the average roll torque, $\overline{T}_{\text{roll}}$, exerted by the lines on the boat, is imposed to avoid excessive roll angles;
e) the average electrical power generated by the KE-yoyo, $\overline{P}^{\text{KE-yoyo}}$, must be higher than the power required by the onboard auxiliaries, $P_{\text{aux}}^{\text{elt}} \doteq i^{\text{aux}} V^{\text{battery}}$. To this end, a constant value of i^{aux} is considered;
f) the amount of energy generated by the KE-yoyo during the traction phase has to be sufficiently high to supply the electric propellers during the passive phases, while the traction forces on the line collapse and the propellers are employed to keep the boat speed constant;
g) the boat speed v_{boat} must correspond to an equilibrium of the longitudinal forces applied to the boat, i.e. $\dot{v}$ (3) has to be zero;
h) finally, the traction force on each line, equal to $\overline{F}^{\text{c,trc}}/2$, must be lower than the minimal breaking load for the line, with a suitable safety coefficient c_s.

The constraint d) can be taken into account as a constraint on the line force, since the average roll torque can be computed as:

$$\overline{T}_{\text{roll}} = \overline{F}^{\text{c,trc}} \sin(\overline{\theta}) \sin(\overline{\phi}) d_{\text{roll}}, \tag{17}$$

where d_{roll} is the distance, along axis Z, between the KSU and the boat roll center. Constraint f) can be expressed as a minimal average power, $P_{\text{req}}^{\text{elt}}$, that has to be generated by the KE-yoyo during each traction phase. Through straightforward manipulations, $P_{\text{req}}^{\text{elt}}$ can be computed as:

$$P_{\text{req}}^{\text{elt}}(v_{\text{boat}}, \dot{r}_{\text{ref}}^{\text{trac}}, \dot{r}_{\text{ref}}^{\text{pass}}) = v_{\text{boat}}\, F^{\text{R}}(v_{\text{boat}}) \frac{\dot{r}_{\text{ref}}^{\text{trac}}}{\dot{r}_{\text{ref}}^{\text{pass}}} \tag{18}$$

Then, constraints e) and f) can be considered together, by asking that the average generated power is higher than an overall required power, $\overline{P}_{\text{req}}^{\text{elt}}$:

$$\overline{P}_{\text{req}}^{\text{elt}}(v_{\text{boat}}, \dot{r}_{\text{ref}}^{\text{trac}}, \dot{r}_{\text{ref}}^{\text{pass}}) = P_{\text{req}}^{\text{elt}}(v_{\text{boat}}, \dot{r}_{\text{ref}}^{\text{trac}}, \dot{r}_{\text{ref}}^{\text{pass}}) + P_{\text{aux}}^{\text{elt}} \tag{19}$$

All of the generated electrical power that exceeds the value of $\overline{P}_{\text{req}}^{\text{elt}}$ is assumed to be used by the electric propellers, so that the resulting average propelling force, $\overline{F}^{\text{motor}}$, can be computed as:

$$\overline{F}^{\text{motor}} = \eta_{\text{motor}} \frac{\overline{P}^{\text{KE-yoyo}} - \overline{P}_{\text{req}}^{\text{elt}}}{v_{\text{boat}}} \tag{20}$$

The constraint g) can be enforced by imposing, according to (3), that:

$$\overline{F}^{\text{tow}} + \overline{F}^{\text{motor}} - F^{\text{R}}(v_{\text{boat}}) = 0,$$

where (by using (8))

$$\overline{F}^{\text{tow}} = \overline{F}^{\text{c,trc}} \cos(\overline{\phi}) \sin(\overline{\theta}).$$

Finally, the constraint h) can be formulated as:

$$c_s \overline{F}^{\text{c,trc}}/2 \leq \overline{F},$$

where $\overline{F}$ is the minimal breaking load of each cable. The value of $\overline{F}$ grows with the square of the line's diameter, see e.g. [6] for an example related to the composite fiber employed in the KiteNav project. The resulting optimization problem is formulated as follows:

$$\begin{array}{c}
\left(\overline{\theta}^*, \overline{\phi}^*, \dot{r}_{\text{ref}}^{\text{trac}*}, \dot{r}_{\text{ref}}^{\text{pass}*}, v_{\text{boat}}^*\right) = \arg \max\limits_{\overline{\theta}, \overline{\phi}, \dot{r}_{\text{ref}}^{\text{trac}}, \dot{r}_{\text{ref}}^{\text{pass}}, v_{\text{boat}}} v_{\text{boat}} \\
\text{s. t.} \\
\overline{\theta} \leq \theta^{\max} \\
\vec{W}_{e,r} > 0 \\
\dot{r}_{\text{ref}}^{\text{trac}} \leq \bar{\dot{r}} \\
\dot{r}_{\text{ref}}^{\text{pass}} \geq -\bar{\dot{r}} \\
\overline{F}^{\text{c,trc}} \sin(\theta) \sin(\phi) d_{\text{roll}} \leq \overline{T}_{\text{roll}} \\
\overline{P}^{\text{KE-yoyo}} \geq \overline{P}_{\text{req}}^{\text{elt}}(v_{\text{boat}}, \dot{r}) \\
\overline{F}^{\text{tow}} + \overline{F}^{\text{motor}} - F^{\text{R}}(v_{\text{boat}}) = 0 \\
c_s \overline{F}^{\text{c,trc}}/2 \leq \overline{F}
\end{array} \tag{21}$$

The numerical values of the parameters employed in this paper are reported in Table I and they are related to the boat prototype of the KiteNav project, equipped with a large 160-m^2 area kite. The optimization problem (21) has been solved, by using the MatLab® function `fmincon`, for $\Theta \in [0, 180°]$, so that any boat direction w.r.t. the wind direction is considered, and with three different values of current i^{aux} used by the boat auxiliaries: $i^{\text{aux}} = 0$ (no auxiliaries), $i^{\text{aux}} = 1\,\text{kW}$ and $i^{\text{aux}} = 2\,\text{kW}$. The obtained results are shown in Fig. 9(a)-(d). In particular, Fig. 9(a) shows the speed v_{boat}^* achievable by the boat as a function of Θ: as suggested by physical intuition, the maximal speed is obtained when the boat direction is roughly perpendicular to the wind direction. The kite optimal position, in terms of average angles $\overline{\theta}^*$ and $\overline{\phi}^*$, and the optimal line speed in the traction phase, $\dot{r}_{\text{ref}}^{\text{trac}*}$, are shown as a function of Θ in Fig. 9(b)-(d). It can be noted that for $\Theta = 0°$ and up to $\Theta \simeq 150°$ the line speed is zero or very low (the minimal needed to supply the auxiliaries), meaning that boat propulsion is achieved mainly by the towing forces exerted by the lines on the boat. Then, for higher

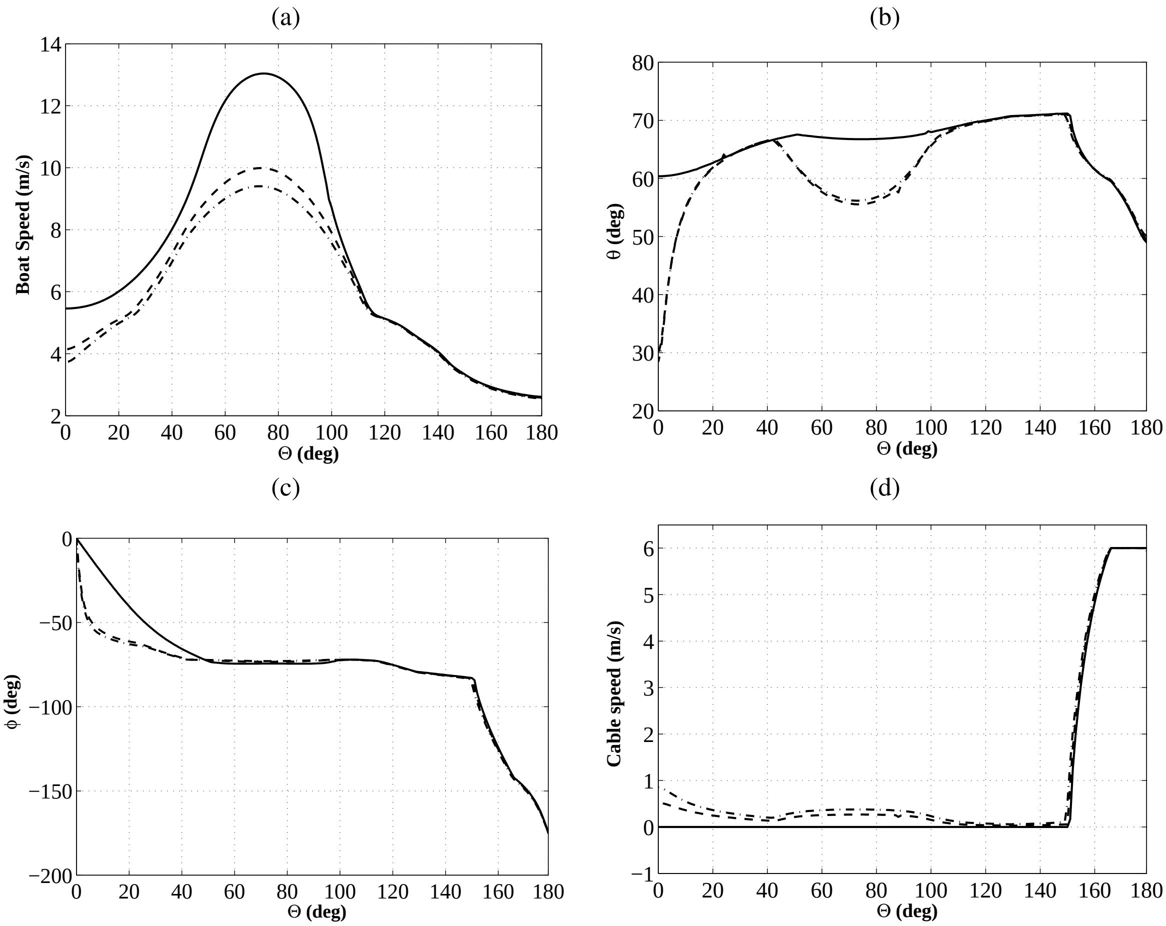

Fig. 9. Optimal operating conditions for a hybrid kite boat as a function of angle Θ between the boat direction and the wind direction. Solid, dashed and dash dotted lines show results for value of $P_{\text{aux}}^{\text{elt}}$ of, respectively, 0, 1 and 2 kW. (a) Maximum achievable speed v_{boat}^*, (b) angle $\overline{\theta}^*$, (c) angle $\overline{\phi}^*$ and (d) line unrolling speed $\dot{r}_{\text{ref}}^{\text{trac}*}$

values of Θ, up to 180° (i.e. when the boat moves straight in upwind direction), the line speed is higher, since the KE-yoyo is used to generate electricity that supplies the electric propellers. As a result, a completely green naval propulsion is obtained regardless of the wind direction. In the case of no electrical power required for on board auxiliary use and in the presence of a wind speed which, according to the employed wind shear model at the kite operating altitude, is about 7-8 m/s, the boat speed values range from 5.5 m/s (with $\Theta = 0°$, downwind navigation) to 13 m/s (with $\Theta = 80°$, crosswind navigation) to 2.5 m/s (with $\Theta = 180°$, upwind navigation). From the results reported in Figures 9(a) and (d), some more considerations on the impact of generating electricity with the KE-yoyo systems can be drawn. In particular, it can be noted that the generation of electric energy through the KE-yoyo cycles does not cause a significant decrease of boat speed only in the range $\Theta \simeq 120° - 180°$, while in the range $\Theta \simeq 0° - 120°$, the generation of even a small electric power, to be used for on board auxiliaries, through the KE-yoyo causes a reduction of about 30% of the achievable boat speed. As a matter of fact, the generation of electric energy to be used for on board auxiliaries use can be more conveniently obtained using underwater turbines, leading for example to only 2-3% reduction of the achievable boat speed, in the case of 2 kW power generation.

A comparison of these results can be made with experimental data obtained during the sea tests performed on the boat employed in the KiteNav project (see [14]). The boat was 39 feet long and weighted 12 tons. The boat was not equipped for electric propulsion, so that only angles Θ between the boat direction and the wind direction in the range 0°-80° are considered, where, as just noted, the maximal boat speeds are obtained without requiring electric energy generation. The employed kite was a 16 m^2 commercial kite used for kite surfing and the line length was 200 m. The wind speed at 3 m over the sea was 3.3 m/s. Under these conditions, boat speeds of about 1.5-1.7 m/s have been obtained during the experiments, with angles between the boat and the wind directions in the considered range. These speeds values are well consistent with the ones predicted for the considered experimental conditions by the method presented in this section and reported in Fig. 10.

V. Control design and simulation results

The results of Section IV have been obtained by using a simplified model of the overall system, composed by the KSU, the batteries and propellers, and the boat. As a matter of fact, the overall system has complex unstable nonlinear

TABLE I
NUMERICAL VALUES USED IN THE OPTIMIZATION PROBLEM

Kite and boat parameters		
A	160	Kite characteristic area (m^2)
d_l	0.02	Diameter of a single line (m)
E	8	Kite aerodynamic efficiency
C_L	1.1	Kite lift coefficient
$C_{D,l}$	1	Line drag coefficient
M	12	Boat mass (t)
ρ	1.2	Air density (kg/m^3)
$\overline{r}$	200	Average line length (m)
Δr	50	Line length variation (m)
d_{roll}	1.5	Vertical distance between the KSU and the boat roll center (m)
η_{KSU}	0.95	KSU electrical and mechanical efficiency
$\eta_{\text{KE-yoyo}}$	0.7	KE-yoyo cycle efficiency
η_{motor}	0.54	Electric motor and propellers' efficiency
Wind shear model parameters		
$\overline{W}$	7.5	Reference wind speed (m/s)
$\overline{Z}$	70	Reference height (m)
β	0.15	Power-law coefficient
Constraints		
$\overline{T}_{\text{roll}}$	$1\,10^5$	Maximal roll torque (Nm)
$\theta^{\max}$	80	Maximal value of $\overline{\theta}$ (°)
$\lvert\dot{\overline{r}}\rvert$	6	Maximal line speed (m/s)
$\overline{F}$	35	Minimal line breaking load (tons)
c_s	5	Safety factor

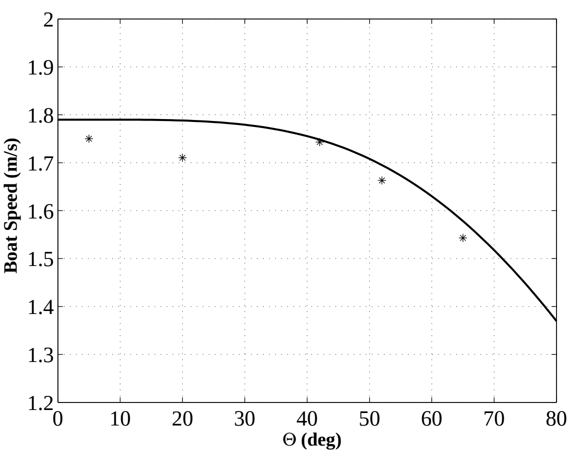

Fig. 10. Maximum achievable speed (solid line) as a function of angle Θ between the boat and the wind directions, computed with the proposed method by considering the same conditions as those encountered during experiments in the KiteNav project, and comparison with experimental data (asterisks).

dynamic behaviors, subject to hard operational constraints, and a feedback control system has to be designed for its stabilization and performances optimization. As far as control of ground-based HAWE generators is concerned, there are several studies in the literature, concerned with the design of an algorithm able to satisfy the above-mentioned requirements. The proposed approaches include Nonlinear Model Predictive Control (NMPC) [1], [2], [7], [8], adaptive control [18] and evolutionary robotics techniques [19]. As regards the control design for naval applications of HAWE, [10], [11] explore the case of pure boat towing, while there are actually no contributions in the literature, concerned with the control of a hybrid kite boat like the one considered here. In order to tackle this problem, a control design strategy is presented in this Section, based on the nonlinear dynamical model of the hybrid kite boat described in Section III-A. The approach is derived from the one described e.g. in [8]; in particular, local PID controllers are employed for the electric propellers and the line speed of the KE-yoyo, while a Nonlinear Model Predictive Control (NMPC) technique is designed to control the kite flight. NMPC has been chosen as control technique due to its ability to systematically deal with the presence of relevant state and input constraints in the system's dynamics. Then, it will be shown that the designed control system acting on the nonlinear dynamical model of the hybrid kite boat actually achieves performances very close to the optimal ones, derived in Section IV.

A. NMPC design

In NMPC (see e.g. [13], [20]), the control move computation is performed at discrete time instants, defined on the basis of a suitably chosen sampling period Δ_t. At each sampling time $t_k = k\Delta_t,\ k \in \mathbb{N}$, the control move is computed through the optimization of a performance index of the form:

$$J(U, x(t_k)) = \int_{t_k}^{t_k+T_p} L(\tilde{x}(\tau), \tilde{u}(\tau))d\tau \qquad (22)$$

where $T_p = N_p\Delta_t,\ N_p \in \mathbb{N}$ is the prediction horizon, $\tilde{x}(\tau)$ is the state predicted inside the prediction horizon according to the state equation (11), using as initial state the measured value $\tilde{x}(t_k) = x(t_k)$ and as input the piecewise constant control input $\tilde{u}(t)$ belonging to the sequence $U = \{\tilde{u}(t)\},\ t \in [t_k, t_{k+T_p}]$ defined as:

$$\tilde{u}(t) = \begin{cases} \bar{u}_i,\ \forall t \in [t_i, t_{i+1}],\ i = k, \ldots, k + T_c - 1 \\ \bar{u}_{k+T_c-1},\ \forall t \in [t_i, t_{i+1}],\ i = k + T_c, \ldots, k + T_p - 1 \end{cases} \qquad (23)$$

where $T_c = N_c\Delta_t,\ N_c \in \mathbb{N},\ N_c \leq N_p$ is the control horizon. The stage cost $L(\cdot)$ in (22) has to be suitably designed on the basis of the performance to be obtained. In particular, NMPC has been used with two different philosophies in the existing studies on control of high-altitude generators with kites, i.e. either with a tracking formulation [2] or with an economic formulation [7], [8]. In tracking NMPC, an optimal flying path is pre-computed off-line, maximizing the desired performance among all periodic trajectories, and then the stage cost $L(\cdot)$ is chosen in order to track such an optimal trajectory. Even if the optimal flying orbit is computed by taking into account the system's operational constraints, the latter must still be included in the tracking problem, in order to cope with the presence of uncertainty and disturbances. In economic NMPC, no pre-computed orbit is used, but the on-line control problem is designed so to directly maximize the desired performance, subject to the operational constraints. In principle, the system's trajectories resulting from an economic NMPC approach might yield better performance with respect to a tracking NMPC approach, since they are not constrained to be periodic, however with economic NMPC there is generally no a-priori guarantee of stability, thus this aspect has to be checked a posteriori. As a matter of fact, both approaches proved to be effective in the context of kite control. An economic NMPC approach is adopted here, and the performance to be optimized is the matching between the optimal operating conditions (derived with the simplified equations in Section IV) and the actual operating conditions. Therefore, function $L(\cdot)$ is chosen as:

$$L(\tilde{x}(\tau),\tilde{u}(\tau)) = \left[(\tilde{\theta}(\tau)-\overline{\theta}^*(\Theta,P_{\text{aux}}^{\text{elt}}))^2+(\tilde{\phi}(\tau)-\overline{\phi}^*(\Theta,P_{\text{aux}}^{\text{elt}}))^2\right] \quad (24)$$

i.e. the distance between the predicted values of θ and ϕ and their optimal average values, computed by solving (21) for the actual values of Θ and $P_{\text{aux}}^{\text{elt}}$. Finally, the following operational constraints, described in Section IV, have been included:

$$\begin{array}{c}\theta \leq \theta^{\max} \\ F^{\text{c,trc}}\sin(\theta)\sin(\phi)d_{\text{roll}} \leq \overline{T}_{\text{roll}},\end{array} \quad (25)$$

as well as constraints on the input variable, that account for the actuator physical limitations in both maximal values and maximal rate of variation:

$$\begin{array}{c}|\psi(t)| \leq \overline{\psi} \\ |\dot{\psi}(t)| \leq \overline{\dot{\psi}}\end{array} \quad (26)$$

The NMPC law is then computed by using a receding horizon strategy:

1) At time instant t_k, get $x(t_k)$.
2) Solve the optimization problem:

$$\min_{U} \quad J(U,x(t_k)) \quad (27a)$$

$$\text{subject to} \quad (27b)$$

$$\tilde{x}(t_k)=x(t_k) \quad (27c)$$

$$\dot{\tilde{x}}(t)=f(\tilde{x}(t),u(t),\Theta(t),0,i_{\text{aux}}(t),\dot{r}_{\text{ref}},v_{\text{boat}})\ \forall t\in[t_k,t_{k+T_p}] \quad (27d)$$

$$\tilde{x}(t)\in\mathbb{X},\ \tilde{u}(t)\in\mathbb{U}\ \forall t\in[t_k,t_{k+T_p}] \quad (27e)$$

3) Apply the first element of the solution sequence U to the optimization problem as the actual control action $u(t_k)=\tilde{u}(t_k)$.
4) Repeat the whole procedure at the next sampling time t_{k+1}.

The constraints in (27e) include (25)-(26), as well as technical constraints that force the kite to go along "figure eight" trajectories, in order to prevent the lines from wrapping one around the other. For more details on this NMPC approach, the interested reader is referred to [7], [8]. The control law results to be a nonlinear static function of the system state x, of the boat direction Θ w.r.t. the nominal wind direction, of the power required by the boat auxiliaries, $P_{\text{aux}}^{\text{elt}}$, and of the wind conditions, in terms of the wind shear model parameters $\overline{Z}$, $\overline{W}$ and β:

$$\psi(t_k)=\kappa(x(t_k),P_{\text{aux}}^{\text{elt}},\Theta,\overline{Z},\overline{W},\beta) \quad (28)$$

In practice, a "fast" NMPC implementation is required to ensure that the control move is computed within the employed sampling time, of the order of 0.2 s. This can be obtained by using efficient Model Predictive Control techniques (see e.g. [21] and the references therein).

B. Controlled system results

In this subsection, some results are reported on the performances of the designed control system, using the nonlinear dynamical model of the hybrid kite boat resumed in Section III-A. Wind turbulence is taken into account by adding a uniformly distributed random signal to the nominal wind in all three directions X, Y, Z, with a maximal amplitude of 2.5 m/s (i.e. approx 35% of the wind speed at the kite target operating altitude). The employed numerical values of the system and control parameters are reported in Tables I-II. The kite aerodynamic coefficients are computed, in the numerical simulations, as a function of the angle of attack, as described by [7] and [8]. The values of the boat speed, v_{boat}^*, and of the line speed, $\dot{r}_{\text{ref}}^{\text{trac}*}$, $\dot{r}_{\text{ref}}^{\text{pass}*}$, and the target values $\overline{\theta}^*$ and $\overline{\phi}^*$ for the NMPC controller (see (24)) correspond to the optimal values computed, as described in Section IV, for the considered values of Θ and $P_{\text{aux}}^{\text{elt}}$. In particular, the cases $\Theta=0°$, $\Theta=80°$ and $\Theta=180°$ have been considered, all with $P_{\text{aux}}^{\text{elt}}=2$ kW (see Table II). Fig. 12 shows the obtained kite and boat trajectories during a simulation of 600 s, with direction $\Theta=80°$. The value assumed by θ and ϕ angles are shown in Fig. 13 and 14: it can be noted that the average values during the traction phases are $\overline{\theta}=55°$ and $\overline{\phi}=-78°$, quite close to the optimal ones (i.e. $\overline{\theta}^*=56°$ and $\overline{\phi}^*=-75°$, see Table II and Fig. 9) even in the presence of the considered wind turbulence. Fig. 11 shows the course of the input variable $\psi(t)$ during part of the simulation. It can be noted that both input saturation and input rate constraints are satisfied by the employed predictive controller. Similar results have been obtained for the cases $\Theta=0°$ and $\Theta=180°$.

As regards the electric power, the energy production is sufficient to supply the onboard auxiliaries and the electric propellers, thus confirming the results of the optimization study carried out in this paper: in fact, the battery state of charge $Q(t)$ (reported in Fig. 15) oscillates between 95% and 100%, after the initial transient from the starting value of 80%.

TABLE II
MODEL AND CONTROL PARAMETERS EMPLOYED FOR THE NUMERICAL SIMULATIONS WITH $\Theta=0°, 80°, 180°$

V^{battery}	300	Battery voltage (V)
C^{battery}	50	Battery capacity (Ah)
Δ_t	0.2	Sample time (s)
N_c	1	Control horizon (steps)
N_p	10	Prediction horizon (steps)
$\dot{r}_{\text{ref}}^{\text{pass}*}$	-6	Line speed - passive phase (m/s)
$\overline{\psi}$	6°	Input constraints
$\overline{\dot{\psi}}$	9 °/s	
$P_{\text{aux}}^{\text{elt}}$	2	Electrical power for onboard equipments (kW)
$\Theta=0°$		
$\dot{r}_{\text{ref}}^{\text{trac}*}$	0.85	Line speed - traction phase (m/s)
v_{boat}^*	3.73	Target boat speed (m/s)
$\overline{\theta}^*$	28.5	Target θ value (°)
$\overline{\phi}^*$	0.0	Target ϕ value (°)
$\Theta=80°$		
$\dot{r}_{\text{ref}}^{\text{trac}*}$	0.38	Line speed - traction phase (m/s)
v_{boat}^*	9.3	Taget boat speed (m/s)
$\overline{\theta}^*$	51	Target θ value (°)
$\overline{\phi}^*$	-75	Target ϕ value (°)
$\Theta=180°$		
$\dot{r}_{\text{ref}}^{\text{trac}*}$	6.0	Line speed - traction phase (m/s)
v_{boat}^*	2.8	Target boat speed (m/s)
$\overline{\theta}^*$	49	Target θ value (°)
$\overline{\phi}^*$	-180	Target ϕ value (°)

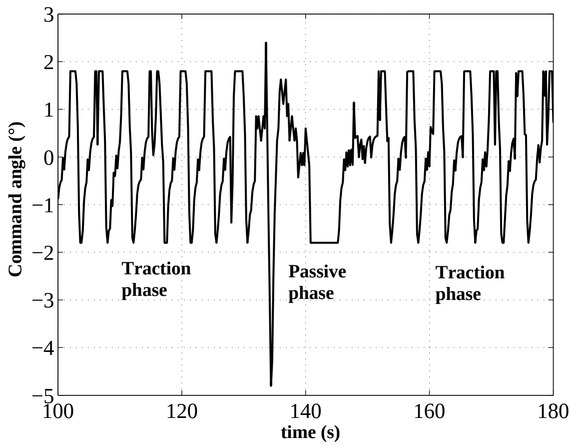

Fig. 11. Simulation results: example of the course of the input variable $\psi(t)$ obtained with $\Theta = 80°$, during traction and passive phases.

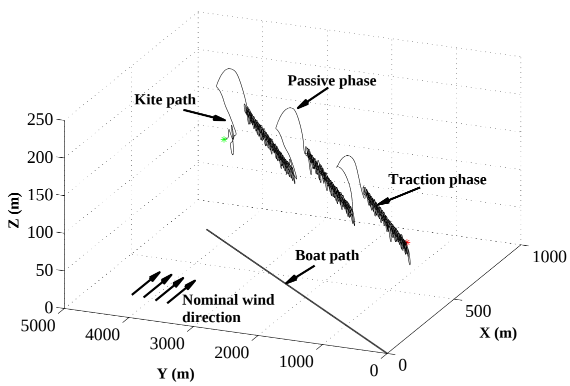

Fig. 12. Simulation results: boat and kite trajectories obtained with $\Theta = 80°$. Boat starting position: (X, Y, Z)=(0,0,0).

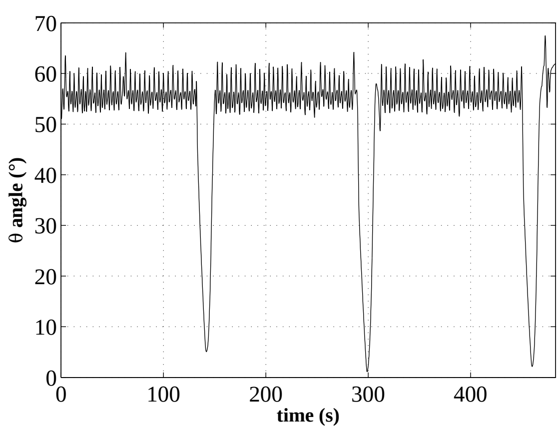

Fig. 13. Simulation results: course of angle θ obtained with $\Theta = 80°$.

Finally, the achieved boat speed with the designed control law resulted to be 3.5 m/s for $\Theta = 0°$, 9.3 m/s for $\Theta = 80°$ and 2.8 m/s for $\Theta = 180°$, very close to the maximal ones predicted by the optimization method of Section IV.

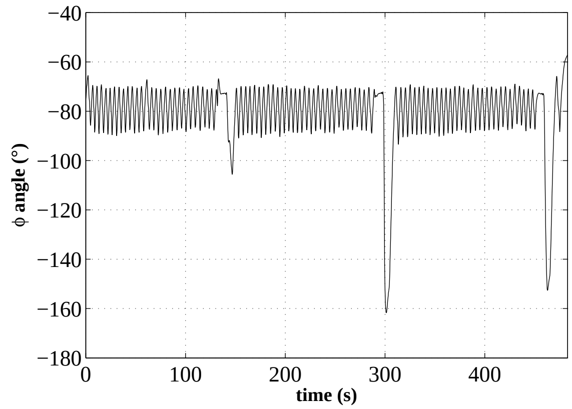

Fig. 14. Simulation results: course of angle ϕ obtained with $\Theta = 80°$.

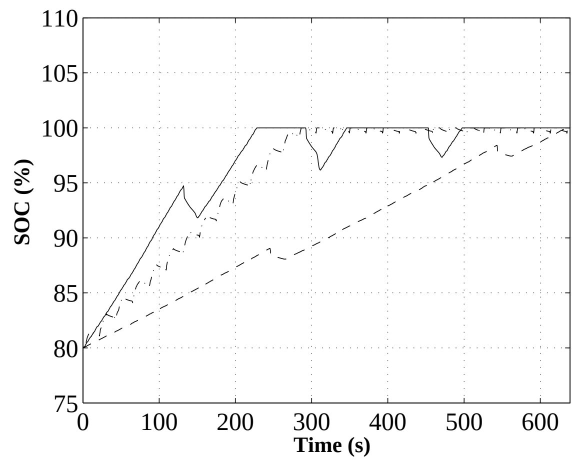

Fig. 15. Simulation results: battery state of charge obtained with $\Theta = 0°$, $80°$, $180°$, dashed, solid and dash-dotted lines, respectively.

VI. Conclusions

The paper presented a study on the application of Kitenergy technology for marine transportation. A hybrid kite boat has been considered, i.e. a boat equipped with a Kitenergy generator which can propel the boat by means of both direct towing forces and generated electricity, to be used by electric propellers. A constrained optimization problem has been formulated, by using a simplified system model, and solved numerically in order to compute the system operating conditions that maximize the boat speed. Then, numerical simulations have been carried out, by using a predictive control strategy and a realistic dynamical model of the system, to assess the feasibility of the computed optimal solutions, also in the presence of wind turbulence. The obtained results demonstrate the potentials of hybrid kite boats to achieve completely green naval transportation.

Acknowledgment

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Lorenzo Fagiano (M'07) received the M.S. in Automotive Engineering in 2004 and the Ph.D. in Information and System Engineering in 2009 from Politecnico di Torino, Italy. In 2005 he worked for Fiat Research Centre, Italy, in the field of active vehicle systems. In 2007 he spent a three-months visiting period in the Optimization for Engineering Center (OPTEC) of the Katholieke Universiteit Leuven. Lorenzo Fagiano is actually a Marie Curie fellow at Politecnico di Torino and a visiting researcher at the University of California, Santa Barbara. His current research interests include high-altitude wind energy generation using controlled tethered wings, model predictive control, polynomial chaos expansions, set membership approximation, and automotive control systems. Lorenzo Fagiano is co-author of about 60 papers published in international journals, conference proceedings and book chapters. He is recipient of the ENI award "Debut in Research" prize 2010, of the Maffezzoni prize 2009 and of a Marie Curie International Outgoing Fellowship.

Mario Milanese (M'90-SM'04) graduated in Electronic Engineering at Politecnico di Torino, Italy, in 1967. From 1968 to 1972 he was Teaching Assistant at Politecnico di Torino, from 1972 to 1980 Associate Professor of System Theory at Università degli Studi di Torino. From 1980 to 2010, he has been Full Professor of System Theory at Politecnico di Torino. From 1982 to 1987 he was the head of the Dipartimento di Automatica e Informatica at Politecnico di Torino. At present he is with Kitenergy, a start-up that he founded in 2010. His research interests include robust identification, prediction and control of uncertain systems, and applications to biomedical, automotive, aerospace, financial and environmental problems. He is the author of about 250 papers in international journals and conference proceedings. He is the editor of the books "Robustness in Identification and Control", Plenum Press, 1989 and "Bounding Approaches to System Identification", Plenum Press, 1996. He has been involved in several national and international projects and in several research contracts in collaboration with Italian and European companies. He is the inventor of several patents in automotive and wind energy fields.

Valentino Razza received the Bachelor's degree and the Master's degree in computer engineering at the Politecnico di Torino, Italy, in 2006 and 2008, respectively. He has been working towards the Ph.D. degree in System engineering at the Dipartimento di Automatica ed Informatica, Politecnico di Torino, since January 2009. His main research interests includes constrained robust control and identification of non-linear systems.

Mario Bonansone received the Bachelor's degree in automation engineering in 2005, and the Master's degree in mechatronic engineering in 2008, both from Politecnico di Torino, Italy. He has been working in Modelway S.r.l. since March 2011. From March 2009 to March 2011, he was an assistant researcher in the Dipartimento di Automatica e Informatica, Politecnico di Torino. His current activities include control of Kitenergy system, identification, design and development of control systems for industrial applications.