Feed-Forward Control of Kite Power Systems

Uwe Fechner and Roland Schmehl

E-mail: `u.fechner@tudelft.nl`
Delft University of Technology, Klyverweg 1, 2629HS Delft, The Netherlands

Abstract. Kite power technology is a novel solution to harvest wind energy from altitudes that can not be reached by conventional wind turbines. The use of a lightweight but strong tether in place of an expensive tower provides an additional cost advantage, next to the higher capacity factor. This paper describes a method to estimate the wind velocity at the kite using measurement data at the kite and at the ground. Focussing on a kite power system, which is converting the traction power of a kite in a pumping mode of operation, a reel-out speed predictor is presented for use in feed-forward control of the tether reel-out speed of the winch. The results show, that the developed feedforward controller improves the force control accuracy by a factor of two compared to the previously used feedback controller. This allows to use a higher set force during the reel-out phase which in turn increases the average power output by more than 4 %. Due to its straightforward implementation and low computational requirements feedforward control is considered a promising technique for the reliable and efficient operation of traction-based kite power systems.

1. Introduction

Wind energy is a major source of renewable energies, but conventional wind-turbines are coming to physical and economic limits in terms of size, height and cost reduction. Airborne wind energy devices could overcome some of these limitations: With a tethered wing it is easy to reach 400 to 600 meters of height[1] where the wind is stronger and steadier, and the fact that for an airborne wind energy system no tower is needed could help to reduce the costs significantly.

Optimized control systems are crucial for the success of airborne wind energy systems. Very simple kite control systems already work [2], but they show only a limited performance [3]. Non-linear model predictive control was suggested in [4], but currently available models that have a good accuracy are not fast enough for full model predictive control. Therefore we suggest to use feed-forward control as an intermediate step that does not need much computational power while still achieving a good control performance.

The focus of this paper is the application of feed-forward control on pumping mode airborne wind energy systems. At low wind velocities both the reel-out speed and the tether force need to be increased when the wind is getting stronger. When the maximal tether force is reached for which the system was designed and the wind still increases, then the reel-out speed has to be increased even faster to keep the force within the allowed limits. Optimizing this mode of operation for constant tether force is the chief goal of this work. In Schreuder [5] a gain scheduled feed-back controller was suggested for this purpose. One of the results of Schreuder [5] was that very fast force sensors and motor controllers are needed to avoid instabilities due to system delays, unless a compliant element (e.g. a piece of bungee cord) is attached to the tether. But adding a compliant element has severe disadvantages: It reduces the efficiency of

the system and it increases the system complexity. Therefore, in this paper we suggest to use feed-forward control to achieve a good system performance even in the presence of a slow and simple feed-back loop.

First the overall control system structure is described. Then the estimators for the wind speed at the height of the kite and for the required reel-out speed are described in detail. Next, measurement and simulation results are shown. Finally conclusions are presented.

2. Computational approach

In Fig. 1 an overview of the winch control system is given, showing only the components needed at high wind speeds, when the system is operating in constant force mode. The kite
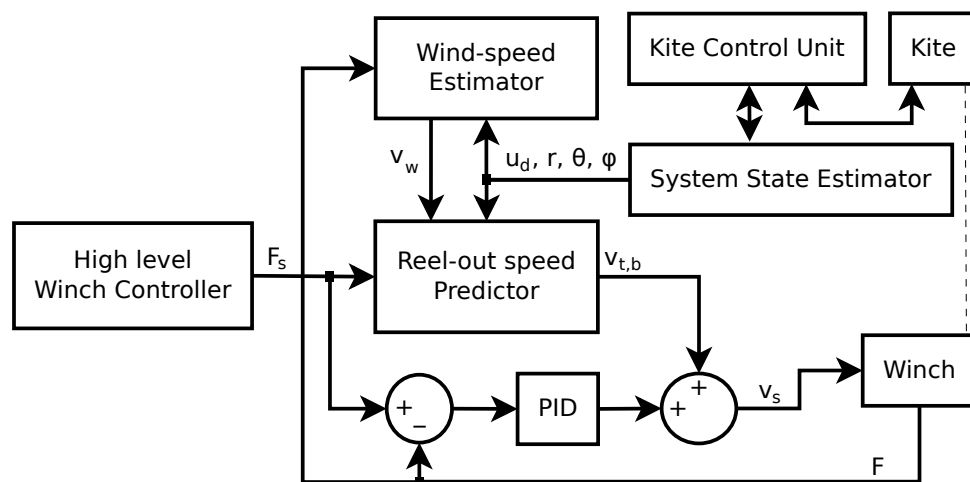

Figure 1. Overall structure of the software and hardware components of the force-control loop of a pumping kite power system. The set force F_s is the main input, the set speed v_s the control output. The wind speed at the height of the kite v_w is estimated as described in this paper. The relative depower value u_d together with the kite position vector r, θ, ψ is calculated from the "System State Estimator", which estimates the system state based on data from sensors in the kite control unit and attached to the kite itself. The reel-out speed predictor calculates the baseline value of the reel-out speed $v_{t,b}$. The measured tether force F, provided by the winch is used for the feed-back PID controller and the wind speed estimator.

is connected to the kite control unit which can steer the kite by pulling differentially at the right and left steering tape and can change the angle of attack. The kite is equipped with a Global Navigation Satellite System (GNSS) position sensor and an inertial measurement unit to determine its orientation. The system state estimator calculates the best estimate of the position and orientation of the kite, based on the current and past measurements. It also takes the data from additional, ground based sensors into account. One of these sensors is the reel-out length as reported from the winch.

Based on the current tether force F as measured at the winch and the kite position and depower[1] settings as reported from the system state estimator, the wind speed estimator calculates the wind speed v_w at the height of the kite.

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[1] The depower settings u_d are a value between 0 and 100 %. They are proportional to the line-length difference between the lines attached to the front and the back of the kite. This line length difference is changing the angle of attack and thus the lift-over-drag ratio. The minimal depower value is equivalent to the highest possible L/D ratio, the maximal depower value is equivalent to the lowest possible L/D ratio.

The reel out speed predictor uses this estimated wind speed in addition to the system state to predict the reel-out speed that is needed to achieve the desired tether force F_s as calculated by the high-level winch controller. To compensate the prediction errors, an additional feedback loop is implemented: The set value and the actual value of the tether force are subtracted and this error value is used by a PID controller to implement the feedback loop.

2.1. Apparent wind velocity

To derive the formulas for the wind speed estimation and reel-out speed prediction the kite power theory as described in [6] is used. The kite is assumed to fly on a half sphere with the radius of the tether length. In addition, a straight tether and a quasi-steady equilibrium are assumed. The position of the kite is described using spherical coordinates in the wind reference frame: The x-axis of this reference frame is pointing downwind, the z-axis upwards and the origin is at the point where the tether exits the ground-station as shown in Fig. 2. The apparent air velocity $\mathbf{v}_a$ as seen from the kite is defined as:

$$\mathbf{v}_a = \mathbf{v}_w - \mathbf{v}_k, \tag{1}$$

where $\mathbf{v}_w$ is the wind velocity at the kite. When the kite velocity $\mathbf{v}_k$ is decomposed into a radial and a tangential component Eq. (1) can be written as [6]:

$$\mathbf{v}_a = \mathbf{v}_w - \mathbf{v}_{k,r} - \mathbf{v}_{k,\tau} \tag{2}$$

Under the assumption of a straight, rigid tether, the radial kite velocity $\mathbf{v}_{k,r}$ is equal to the tether reel-out speed:
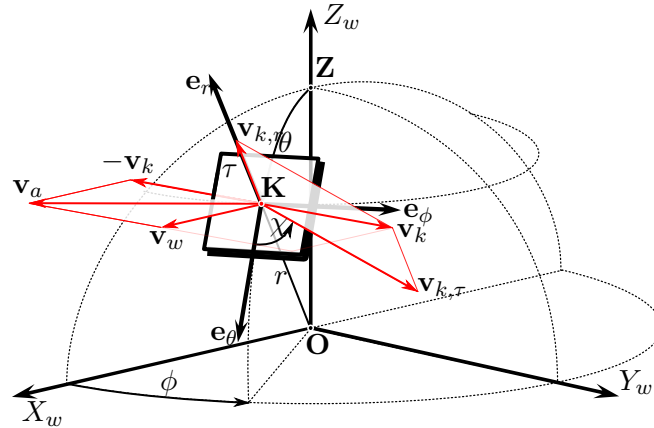
$$\mathbf{v}_{k,r} = \mathbf{v}_t \tag{3}$$

Figure 2. Definition of the apparent wind velocity $\mathbf{v}_a = \mathbf{v}_w - \mathbf{v}_k$. Decomposition of the kite velocity $\mathbf{v}_k$ into radial and tangential components $\mathbf{v}_{k,r}$ and $\mathbf{v}_{k,\tau}$, respectively. The course angle χ is measured in the tangential plane τ, the spherical coordinates (r, θ, ϕ) are defined with respect to the wind reference frame X_w, Y_w, Z_w [6].

Using the spherical coordinates (r, θ, ϕ) and the course angle χ as defined in Fig. 2 we can write [6, Eq. (2.7)]:

$$\mathbf{v}_a = \begin{bmatrix} \sin\theta\cos\phi \\ \cos\theta\cos\phi \\ -\sin\phi \end{bmatrix} v_w - \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} v_t - \begin{bmatrix} 0 \\ \cos\chi \\ \sin\chi \end{bmatrix} v_{k,\tau} \tag{4}$$

The angle θ is related to the elevation angle β as follows:

$$\theta = \frac{\pi}{2} - \beta \tag{5}$$

The lift force of the kite is related to the apparent air velocity v_{a} as follows:

$$F_{\mathrm{L}} = \frac{1}{2} \rho \, C_{\mathrm{L}} \, v_{\mathrm{a}}^2 \, A \, , \tag{6}$$

where C_{L} is the lift coefficient and A the projected surface area[2] of the kite.

2.2. Estimation of the wind speed

The basic idea of the wind speed estimation is that according to Eq. (6) the apparent air velocity v_{a} is related to the lift force F_{L}, and according to Eq. (4) it is also related to the wind speed at the height of the kite. Therefore, if the reel out velocity, the tangential kite velocity and position and the lift force are known, then it should be possible to calculate the wind speed.

By combining Eq. (4) and Eq. (6) and solving for the wind velocity we obtain the following equation:

$$v_{\mathrm{w}} = v_t \Big/ \left(\sin\theta \cos\phi \; - \; \sqrt{-(v_{\mathrm{k},\tau}\sin\chi + v_{\mathrm{w}}\sin\phi)^2 - (v_{\mathrm{k},\tau}\cos\chi - v_{\mathrm{w}}\cos\phi\cos\theta)^2 + \frac{2\,F_L}{C_{\mathrm{L}}\,A\rho}} \right) \tag{7}$$

which cannot be solved analytically but has to be solved numerically.

If the apparent air velocity is not accurately measured[3], then the tether force as measured at the ground can be used to calculate the lift force that is needed in Eq. (7). How this can be done is derived in the following paragraphs.

In a first step, in Eq. (8) the tether force at the kite $F_{t,k}$ is calculated based on the tether force at the ground $F_{t,g}$ and the tether mass, using the elevation angle β and the standard gravity $g = 9.81 m/s^2$ but neglecting the drag forces. The drag forces of the tether will later be added to the kite drag and taken into account in Eq. (12).

$$F_{\mathrm{t,k}} = F_{\mathrm{t,g}} + m_{\mathrm{t}}\, g \, \sin\beta \tag{8}$$

Written in spherical coordinates (r, θ, ϕ), we obtain:

$$\mathbf{F}_{\mathrm{t,k}} = \begin{bmatrix} -F_{t,k} \\ 0 \\ 0 \end{bmatrix} \tag{9}$$

In equilibrium the aerodynamic force vector $\mathbf{F}_{\mathrm{a}}$ must balance the sum of the tether force vector at the kite $\mathbf{F}_{\mathrm{t,k}}$ and the gravity force $m\mathbf{g}$ that is experienced by the kite and the kite control unit:

$$\mathbf{F}_a = -\mathbf{F}_{t,k} - m\mathbf{g} \tag{10}$$

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[2] Area of the shape of the kite, projected on the plane perpendicular to the last tether segment while the depower angle is zero.

[3] Accurate air velocity measurements at a kite are difficult: Pitot tubes often become dirty when the kite is landed. Ultrasonic sensors are too large and heavy for small kite control units.

Using the straight tether assumption this can be written as:

$$\mathbf{F}_a = \begin{bmatrix} F_{t,k} + \sin\theta\; mg \\ -\cos\theta\; mg \\ 0 \end{bmatrix} \tag{11}$$

Because the aerodynamic force F_a is the sum of the lift and the drag force, and because $F_L/F_D = C_L/C_D$ we can calculate the lift force F_L as follows:

$$F_L = \frac{F_a}{\sqrt{1 + \frac{C_D^2}{C_L^2}}} \tag{12}$$

By inserting the result of Eq. (12) into Eq. (7) the wind speed v_w at the height of the kite can be estimated without using any wind sensor but the kite itself.

The coefficients C_L and C_D are a function of the angle of attack, which in turn can be estimated when the depower settings u_d are known.

2.3. Prediction of the required reel-out speed

Once the wind speed at the height of the kite v_w is known, the reel-out speed $v_{t,b}$, that is required to obtain a given tether set-force F_s can be predicted. The set force F_s has to be used for $F_{t,g}$ in Eq. (8). If this is done to calculate the required lift force according to Eq. (12), then the following equation can be used to calculate the baseline speed $v_{t,b}$ of the winch controller:

$$v_{t,b} = v_w \sin\theta \cos\phi - $$
$$\sqrt{-(v_{k,\tau}\sin\chi + v_w\sin\phi)^2 - (v_{k,\tau}\cos\chi - v_w\cos\phi\cos\theta)^2 + \frac{2\; F_L}{C_L\; A\rho}} \tag{13}$$

In order to separate large-scale behaviour from noise and in order to suppress perturbations from the tether and from the wind, a moving average filter with a length of one second was used for filtering the output of the reel-out speed predictor. The filter length was chosen such that the prediction error as shown in Fig. 3 was minimized.

3. Measurement and simulation results

The performance and accuracy of the predictor and controller were benchmarked against a four-point kite model[4] and a tether, discretized by seven segments. Each tether segment is represented by a spring-damper element and aerodynamic line drag. The winch was modelled using an asynchronous generator model. The system model was verified using measurements of our kite power system demonstrator [3], [7].

3.1. Accuracy of the reel-out speed predictor

The prediction error along two power cycles is shown in Fig. 3. The speed v_t was in the range of -8 m/s to 6 m/s, the maximal error was less then 1 m/s, the mean square error was 0.16 m/s and the standard deviation 0.4 m/s.

The errors are caused mainly by the simplifications of the quasi-steady model used to derive Eqns. (7) and (13): A straight, unstretchable tether and the neglect of dynamic force contributions. As shown in the following section, the prediction accuracy of about $\pm7\%$ of the full speed range is sufficient to improve the performance of the force controller significantly.

[4] The four-point kite model will be explained in detail in the paper "Dynamic Model of a Pumping Kite Power System" which shall be submitted to the Journal "Renewable Energy" in 2014.
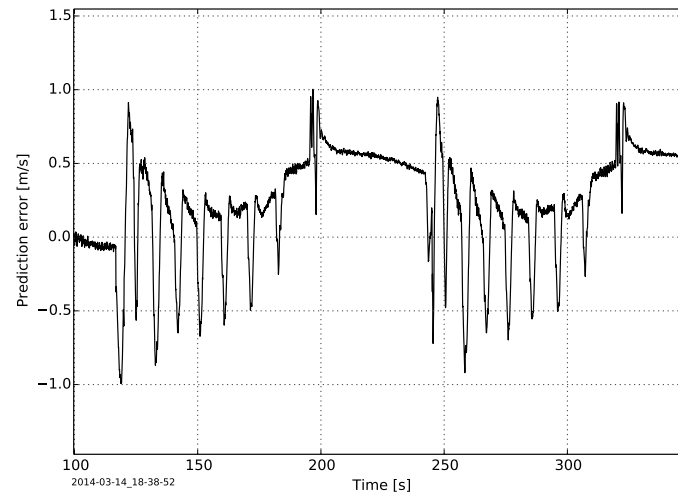
Figure 3. Prediction error of the reel-out speed during two power cycles with feedback control only. The measured force was used as set-force, and the difference between the measured and the predicted reel-out speed is shown. An error of 1 m/s is equivalent to about 7 % of the full range of the reel-out speed, that was used.

3.2. Performance of the force controller

Our kite power system demonstrator was simulated with and without feedforward control for the tether force. A feedback loop delay of 20 ms is assumed, which is about five times faster than the delay of the current demonstrator. This is assumed to be the fastest feedback loop, that can be implemented based on the current state of art. The result without feedforward control is shown in Fig. 4. While flying figures of eight the peak force is about 8.2 % higher than the
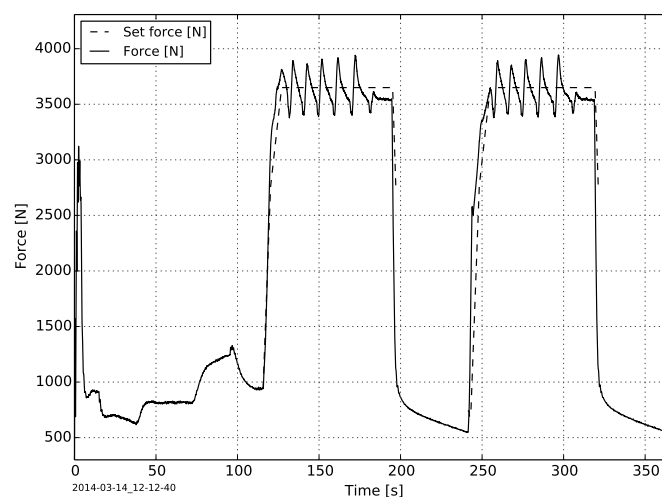

Figure 4. Set force and actual force of two power cycles with feedback control only. Where no set force is shown the controller is operating in constant speed mode. The set force has to be chosen such that the maximal design force of 4000 N is not exceeded.

set force. The average mechanical power is 8399.5 W.

Fig. 5 shows the set force and the actual force of a controller which uses feedforward control in combination with feedback control. Now the peak force is only 4.0 % higher than the set value.
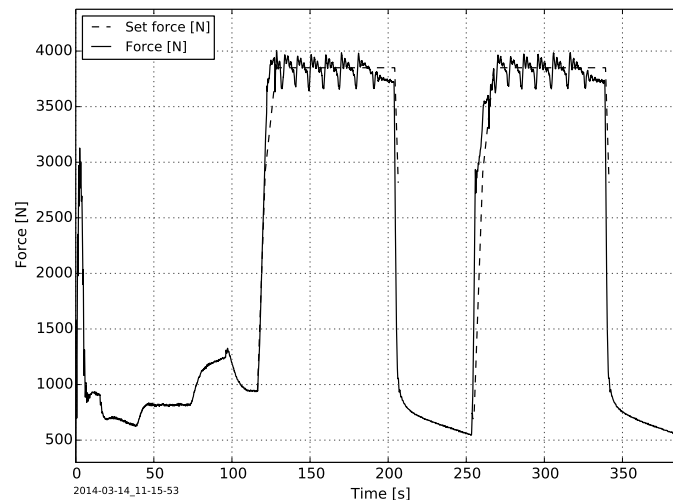
Figure 5. Set force and actual force of two power cycles of the improved controller, using feedforward control.

Therefore the set value could be increased from 3650 N to 3850 N. This results in an average mechanical power of 8777.8 W, which is 4.5 % higher compared to the system which is not using feedforward control.

4. Conclusions

If the aerodynamic properties of a kite are known, then measurements of the force and speed of the winch of a kite-power system can be used to estimate the wind speed at the height of the kite. When the wind speed is known the reel-out speed that is required to obtain a desired set-value of the force can be predicted.

By using the predicted reel-out speed the overshoot of the tether force of a kite power system can be reduced by a factor of two which can improve the average power output at high wind speeds by more than 4 % if a feedback loop with only 20 ms delay is used. If the delay of the feedback loop is higher, than the advantage of using feedforward control is even larger.

Even though further research is needed to prove the robustness of feed-forward control in practice, it is a promising control approach due to its simplicity and low computational requirements.

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