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Dynamic model of a pumping kite power system

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ABSTRACT

Converting the traction power of kites into electricity can be a low cost solution for wind energy. Reliable control of both trajectory and tether reeling is crucial. The present study proposes a modelling framework describing the dynamic behaviour of the interconnected system components, suitable for design and optimization of the control systems. The wing, bridle, airborne control unit and tether are represented as a particle system using spring-damper elements to describe their mechanical properties. Two kite models are proposed: a point mass model and a four point model. Reeling of the tether is modelled by varying the lengths of constituent tether elements. Dynamic behaviour of the ground station is included. The framework is validated by combining it with the automatic control system used for the operation of a kite power system demonstrator. The simulation results show that the point mass model can be adjusted to match the measured behaviour during a pumping cycle. The four point model can better predict the influence of gravity and inertia on the steering response and remains stable also at low tether forces. Compared to simple one point models, the proposed framework is more accurate and robust while allowing real-time simulations of the complete system.

1. Introduction

Wind energy is a major source of renewable energy. However, conventional wind turbines are restricted by physical and economic limits. Airborne wind energy has the potential to overcome some of the limitations, using tethered flying devices to reach altitudes of 400–600 m where the wind is stronger and steadier [1]. The fact that airborne wind energy systems do not require towers reduces the costs per installation significantly.

The focus of this paper is the modelling of airborne wind energy systems that use the traction power of a tethered inflatable wing in a pumping cycle, as described in Refs. [2] and [3]. The main components of such a single-tether kite power system (KPS) are the wing, the kite control unit (KCU) suspended below the wing by means of a bridle system, the tether and the drum-generator module, which is part of the ground station. It is the objective to develop a system model that is real-time capable and of sufficient accuracy for the development and verification of flight path and ground station controllers.

A dynamic model of a two-line kite is derived in Ref. [4]. Variations of the angle of attack are not taken into account and the simplicity of the model allows for an analytical derivation of a state space representation based on four dynamic states. Further expanding on this model, [5] proposed a kite power system model with three degrees of freedom (DOF), in which the kite is represented as a point mass at the end of the straight tether of variable length. Assuming a rigid wing with constant aerodynamic properties, the steering forces are derived as functions of the roll angle.

A discretisation of the tether as a multibody system has been proposed by Ref. [6], using a Lagrangian approach to derive the equations of motion in generalised coordinates. The advantage of this approach is the direct incorporation of constrains which results in a compact problem formulation. This model used rigid tether segments, connected by spherical joints, which is not sufficient for modelling the tether force and implementing the force control loop. In addition it is adding and removing point masses during the simulation to simulate reel-out and reel-in of the tether. According to our experience this causes artificial discontinuities in the model which makes it difficult to implement the force control loop. For the kite it also used a point mass model.

A model that uses a discretised tether with point masses connected by springs was published in Ref. [7]. The aerodynamics of the kite were modelled using the vortex lattice method, which means that it is using an advanced kite model. On the other hand it was not mentioned if the dynamics of the winch were modelled at all and no details were published on the question how reeling in

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Nomenclature

c	damping coefficient of tether segment [Ns/m]
c_0	unit damping coefficient [Ns]
c_s	steering coefficient (one point kite model) [−]
d_t	tether diameter [m]
i_d	relative depower input of kite control unit (0, 1) [−]
i_s	relative steering input of kite control unit (−1, 1) [−]
k	spring constant of tether segment [N/m]
k_0	unit spring constant [N]
$K_{s,D}$	steering-induced drag coefficient [−]
$l_{t,i}$	tether length at beginning of time step i [m]
m_{KCU}	mass of kite control unit [kg]
m_k	mass of kite [kg]
n	number of tether segments [−]
$l_{s,0}$	initial length of tether segment [m]
u_d	relative depower setting of kite control unit (0, 1) [−]
u_s	relative steering setting of kite control unit (−1, 1) [−]
v_o	tether reel-out speed [m/s]
$v_{w,ref}$	horizontal wind velocity at 6 m height [m/s]
z	height of kite or tether segment [m]
$\mathbf{a}$	vector of accelerations of tether particles [m/s^2]
$\mathbf{d}_i$	drag force vector acting on tether segment i
$\mathbf{F}_g$, $\mathbf{F}_s$	vectors of the gravity and steering forces of kite [N]
$\mathbf{F}_L$, $\mathbf{F}_D$	lift and drag force vectors acting on the kite [N]
$\mathbf{p}$	vector of positions of tether particles [m]
$\mathbf{A}$, $\mathbf{B}$	position vectors of the front and top kite particles [m]
$\mathbf{C}$, $\mathbf{D}$	position vectors of the right and left kite particles [m]
$\mathbf{R}$	vector of the residual of the implicit problem/model
$\mathbf{s}_i$	vector from the tether particle i to the particle i + 1 [m]
$\mathbf{s}_{v,i}$	velocity of tether particle $i+1$ relative to particle i [m/s]
$\mathbf{v}_a$	vector of apparent air velocity [m/s]
$\mathbf{v}_{w,k}$	vector of wind velocity at the height of kite [m/s]
$\mathbf{e}_x$, $\mathbf{e}_y$, $\mathbf{e}_z$	unit vectors of the kite-reference frame
$\boldsymbol{Y}$	state vector of the implicit problem/model
α, β	angle of attack and elevation angle [rad]
ρ	air density [kg m^{-3}]

and out was modelled. Other authors presented detailed generator and winch models [5,8], but no or only a very simple model for the kite and the tether.

Coupling fluid and structural dynamic solvers for wind turbine applications has been studied by Refs. [9,10], while fluid–structure interaction methods have been applied to kite aeroelastic behaviour by Ref. [11]. These kind of models might be useful for the design of improved kites, but they are very computational intensive and currently at least one order of magnitude slower than real-time [11].

This paper presents a model where the dynamics of all major system components – the tether, the kite and the generator – are taken into account, with a focus on a novel discretised tether model which allows smooth reel-in and reel-out. It is soft real-time capable and thus suitable for the training of kite pilots and winch operators, but can also be used for software in the loop testing of KPS control systems, the development of estimation algorithms and for the optimization of flight trajectories.

An improved one-point kite model is presented, that allows to change the angle of attack during simulation time and uses look-up tables to calculate the lift and drag as function of the angle of attack. It also takes the increased drag when flying around corners into account. In addition it uses a correction term to match the influence of gravity. This model can already be sufficient for optimizing flight trajectories.

For controller development a four-point kite model is devised, the most simple point mass model that has rotational inertial in all axis. This avoids discontinuities in the kite orientation which make the one-point kite model uncontrollable in curtain flight manoeuvres. In addition it is very close to a fully physical model: Many model parameters like the height and width of the kite and the height of the bridle can just be measured and do not need to be identified. Only the steering sensitivity parameters need to be identified because they depend on the flexibility of the kite which is not explicitly modelled.

This article will first explain the atmospheric model, then the tether model and the two kite models and finally the winch model. Furthermore, the control system is briefly explained. Subsequently a systematic approach for the model calibration is presented, with the goal to match the conditions of a real flight as good as possible.

In the results section major parameters like force, speed, power and flight trajectory as obtained from the point mass model and the four point model are compared with data, measured using the Hydra kite of Delft University of Technology. Finally conclusions are drawn about the performance and accuracy of the described models and which improvements are still needed.

2. Computational approach

One of the requirements when building the model was, that it has to be (soft-) real-time capable. On the other hand, the programming effort should be limited and it should be easy to adapt the model to different kite power systems. It was found that high-level modelling tools like Simulink or Modellica were not capable to simulate a discretised tether that is reeling in or out in real-time. Therefore general purpose programming languages are used that make low-level optimizations of the modelling code possible.

We are modelling the kite and the tether as a particle system, using discrete point masses which are connected by spring-damper elements. This has the advantage of a coherent model structure for which efficient mathematical methods for solving the stiff equation system exist [12]. For describing the positions of the particles a ground fixed reference frame is used, where the x-axis is pointing east, the y-axis north and the z-axis upwards. The origin is placed at the ground station.

The state vector of the system was constructed using the states of the tether particles, the states of the kite particles (only needed for the four point kite model, because otherwise the last tether particle also represents the kite) and the scalar states of the winch (generator). Because no accurate, real-time measurements of the wind speed at the height of the kite were available, an atmospheric model, describing the wind profile, was also needed.

2.1. Atmospheric model

To determine the wind speed v_w at the height of the kite and at the height of each tether segment, the power law [13] and the log law [14, p. 19] are used. Input parameters are the ground wind speed $v_{w,ref}$ and the current height z of the kite or tether segment. The ground wind speed used in this paper was measured at $z_{ref} = 6.0$ m. The power law establishes the relationship between v_w and $v_{w,ref}$ as

$$v_{w,exp} = v_{w,ref}\left(\frac{z}{z_{ref}}\right)^{\alpha} \tag{1}$$