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Dynamic Model of a Ground-Controlled Ram-Air Kite System for Ship Propulsion

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The European Union has set a goal to become carbon neutral by 2050 through the European Green Deal. To realize this goal, all sectors of the economy, including shipping, have to become carbon neutral. One way to make shipping carbon neutral is by directly using wind energy for ship propulsion. Different methods for this are sails, Flettner rotors, and kites. Traditional sails rely on heavy masts and capture low-velocity winds near the ocean surface. Kites operate at higher altitudes where wind speeds are substantially higher and more consistent, using lightweight materials that induce low vessel bending moments while producing 5 to 25 times more power than conventional sails [1]. One key advantage of kites is that they can fly cross-wind, achieving much higher apparent wind speed and, thus, thrust. The main disadvantage of kite systems is that they are unstable without active control. To stabilize the system, a controller is needed, and designing such a controller requires an accurate kite model.

This work presents a dynamic model of a ground-controlled ram-air kite system for ship propulsion that combines a rigid body representation of the kite concerning its dynamic behavior with an aerodynamic model of the main wing and two tether-actuated trailing edges. The key innovation of this work is the accurate modeling of trailing edge deformation and twist in a dynamic model capable of real-time. The open-source system model achieves 10 times real-time performance on an Intel Core i9-9980HK while maintaining good accuracy in flight simulations. This was achieved using the symbolic modeling framework ModelingToolkit.jl [2] and the Julia programming language. This modeling framework enables high simulation speed and fast linearization of the model, which will allow the use of modern control design methods, such as model predictive control [3] or machine learning.

1 System Architecture

The kite propulsion system consists of a ram-air kite connected to four tethers, which are controlled by three winches. Two of the tethers are steering lines, each attached to a separate winch, while the remaining two power tethers are connected to a single shared winch (Fig. 1). The two power lines and the two steering lines are modeled as a fixed number of lumped masses, connected with spring damper elements [4]. Steering is achieved through asymmetric deformation of trailing edges and twist in the kite body via steering lines connected to bridle line systems (Fig. 2). A sophisticated control system lets the kite fly cross-wind figures of eight to achieve optimal ship propulsion.

2 Dynamic Model

To describe the flight dynamics, the kite is modeled as a rigid body, using quaternion dynamics for orientation tracking and Euler's equations to govern rotational dynamics:

$$\frac{\delta \mathbf{q}_p^w}{\delta t} = \frac{1}{2}\Omega(\omega_p)\ \mathbf{q}_p^w\ , \quad \mathbf{I}\frac{\delta \omega}{\delta t} + \omega_p \times (\mathbf{I}\omega_p) = \mathbf{T}_\mathrm{k}\ . \tag{1}$$

where Ω is the omega operator [5] and ω_p the angular velocity in principal axes.

Figure 1: Complete kite propulsion system with a boat, three winches to control steering, and the kite.

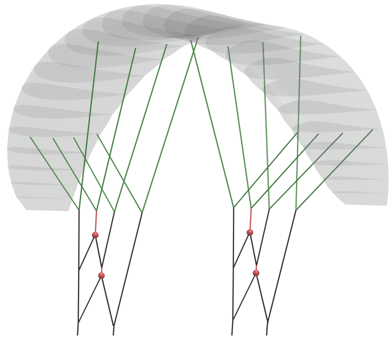

Figure 2: The bridle system of the kite. Each line is modeled as a tether segment. The green segments are simplified by removing extra branches compared to the real kite. The red dots are pulleys, which are held in place by the red tether segments and through which the two connected black segments can freely move. The pulleys are modeled by balancing the spring forces on these two black segments.

3 Aerodynamic Formulation and Deformation

The Vortex Step Method [6] is used to obtain aerodynamic forces and moments in combination with XFOIL-derived 2D polars. The forces and moments are combined with the rigid body equations of motion to derive the differential-algebraic equations describing the kite position and orientation.

The trailing edge and twist deformation are computed by solving a nonlinear problem such that the torque τ_{te} and τ_{le} equal zero.

$$\tau_{\text{te}} = \underbrace{r_{\text{a,te}} \left(\mathbf{F}_{\text{a,te}} \cdot \mathbf{z}_{\text{f}}\right)}_{\text{aero}} + \underbrace{z_{\text{up}} \left\|\mathbf{F}_{\text{r}}\right\|}_{\text{ram}} + \underbrace{r_{\text{te}} \left(\mathbf{F}_{\text{b,4}} \cdot \mathbf{z}_{\text{te}}\right)}_{\text{bridle 4}} = 0\,, \tag{2}$$

$$\tau_{\text{le}} = \underbrace{\sum_{i=1}^{4} r_{\text{b,i}} \left(\mathbf{F}_{\text{b,i}} \cdot \mathbf{z}_{\text{f}}\right)}_{\text{bridles}} + \underbrace{r_{\text{a}} \left(\mathbf{F}_{\text{a}} \cdot \mathbf{z}_{\text{f}}\right)}_{\text{aero}} = 0\,. \tag{3}$$

where r are the different arm lengths of the forces (Fig. 3), $\mathbf{F}_{\text{a,te}}$ the aerodynamic force vector on the trailing edge, z_{up} the position of the joint, $\mathbf{F}_{\text{r}}$ the internal pressure force on the wing cross section area along the joint, r_{te} the arm of the trailing edge bridle connection, $\mathbf{F}_{\text{b,i}}$ the resultant tensile force in bridle line i, $\mathbf{z}_{\text{te}}$ the unit vector perpendicular to the local trailing edge chord line, $\mathbf{F}_{\text{b,i}}$ the spring force in bridle i, r_{a} the arm of the aerodynamic force, $\mathbf{F}_{\text{a}}$ the aerodynamic force vector.

$\mathbf{F}_{\text{a,te}}$ can be found with the pressure distribution on the trailing edge by analysis with XFOIL [7].

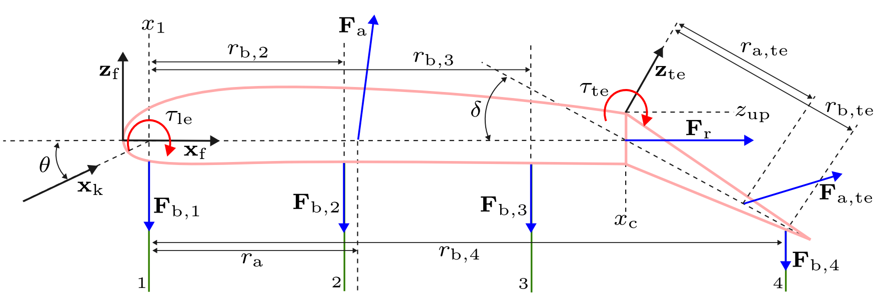

Figure 3: Trailing edge structure, showing the ram force $\mathbf{F}_{\text{r}}$, bridle forces $\mathbf{F}_{\text{b}}$ and aerodynamic forces $\mathbf{F}_{\text{a}}$ contributing to the trailing edge deformation torque τ_{te} about fabric joint $\mathbf{J}_{\text{te}} = (x_{\text{c}}, z_{\text{up}})$ and twist deformation torque τ_{le} about $\mathbf{J}_{\text{le}} = (x_1,\ 0)$. $\mathbf{z}_{\text{f}}$ and $\mathbf{x}_{\text{f}}$ are the foil frame unit vectors.

The kite is steered by asymmetrically pulling the left or right steering tether, which is connected via bridle systems to the kite (Fig. 2). Pulling a tether induces twist θ on the kite body and deformation δ on the trailing edge by rotating the body around the virtual joint $\mathbf{J}_{\text{le}}$ and fabric joint $\mathbf{J}_{\text{te}}$. This deformation increases the drag on the pulled side, generating a torque that yaws the kite.

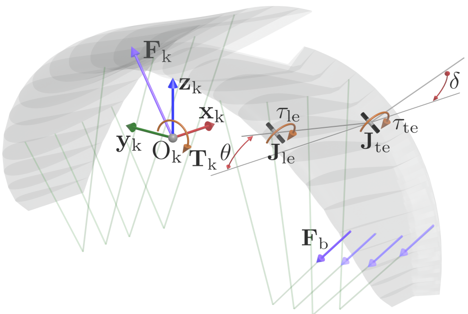

Figure 4: Kite body representation with bridle tether segments force $\mathbf{F}_\mathrm{b}$ causing torques on the leading and trailing edge joints $\mathbf{J}_\mathrm{le}$ and $\mathbf{J}_\mathrm{te}$. θ is the twist angle and δ is the trailing edge deformation angle. The sums of forces and torques on the kite $\mathbf{F}_\mathrm{k}$ and $\mathbf{T}_\mathrm{k}$ cause the rigid kite body to translate and rotate.

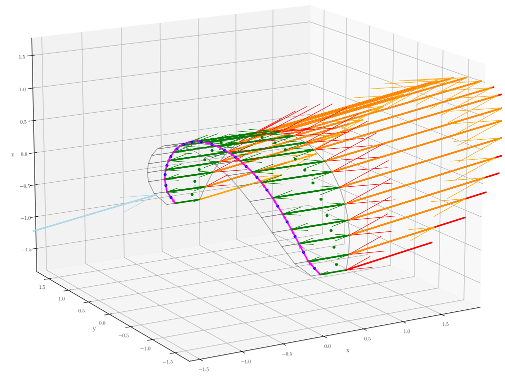

Figure 5: Aerodynamic segmentation in the Vortex Step Method [6]. Apparent wind $\mathbf{v}_a$ is computed relative to panel motion. The user can specify how many segments the kite should have.

4 Validation & Applications

The model was validated against flight test data from the prototype using the "Hyperlink V2 5M" kite. Applications include trajectory optimization, control system development, and validation of simpler, averaged models.

The capabilities of the symbolic modeling framework [2] might allow the implementation of a controller based on linear model predictive control (MPC) that linearizes the model at each time step [3]. The open-source implementation [8] enables community-driven development of kite propulsion systems.

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