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# Symmetric and Asymmetric Aero-Structural Coupled Soft-Wing Kite Simulations

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Simulations are essential for optimizing the design of soft-wing airborne wind energy (AWE) kites. They aid in addressing the inherent design challenges associated with soft-wing kites. For example, generating high force and power necessitates a flat-wing kite, whereas precise and stable steering calls for a wing with substantial curvature. The simulation environment, denoted as virtual wind tunnel (VWT), allows for cheap, fast, safe and sustainable testing of new designs.

Instead of modeling the entire AWE system, only the kite is placed in the simulation domain. The VWT flies with the kite along its trajectory. The flight path is discretized into operating points; for each point, a separate analysis can be made, assuming a quasi-steady state. A boundary condition is placed at the origin that, like the bridle point, holds force in the tether direction but offers no rotational resistance. Without rotational resistance, the yaw, pitch and roll moments at the bridle point must be zero. An equilibrium over the six degrees of freedom is necessary for the simulation to converge to the quasi-steady state. In each operating point, the resulting forces are calculated using an Aero-Structural coupled framework [1]. A structural model is included as soft-wing kites are controlled by morphing the wing and are prone to aero-elastic deformations. A particle system model [1] is loosely coupled to an aerodynamic Vortex-Step Method [2] with integrated pre-computed 2D CFD data [3].

There are operating points, e.g. during the straight part of the reel-in phase, for which one can assume the presence of a symmetry plane at mid-span, i.e. where the left and right half of the kite are equal. The kite is pitch static stable and finds a 'trim-angle' at which the pitch moment is zero. With symmetry, the yaw and roll moments are zero; equilibrium is thus found and the simulation converges.

Without symmetry, the kite must also find an equilibrium position for yaw and roll. The backward swept wing aids positively towards yaw static stability. Finding a roll equilibrium is not trivial, as the anhedral wing shape makes the kite roll statically unstable. The instability requires continuous control input and has limited previous analysis to symmetric cases.

A novel solution is to evaluate a special crosswind flight case in which the kite flies a circular pattern. To remain in a circular flight, the sum of the forces in the radial direction must be zero. In the radial direction, there is a tether force component and a centrifugal force. The centrifugal force equals the sum of the radial components of the tether force and aerodynamic force and must be included because the VWT reference frame is rotating. After some deformation, a constant turning radius is found where the positive aerodynamic and negative centrifugal roll moment contributions cancel out. With a zero roll moment at the bridle point, equilibrium over six degrees is found, enabling the first converging asymmetric VWT simulations.

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