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Induction in Optimal Control of Multiple-Kite Airborne Wind Energy Systems

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Abstract: Multiple-kite Airborne Wind Energy Systems (MAWES) aim to decrease intermittency and cost over conventional wind turbines, while generating more power than other airborne wind energy systems. The purpose of this work is to estimate whether axial and angular induction are relevant phenomena in the modelling of pumping-cycle MAWES with two or more kites. Considering the modelling assumptions, axial induction is a relevant phenomenon and leads to significant changes in design-point, especially with respect to kite mass and secondary tether length. However, angular induction can be neglected in modelling for optimal design and control problems.

Keywords: airborne wind energy, induction, blade-element momentum method, power generation, windmills, optimum, model reduction, systems design

1. INTRODUCTION

Airborne Wind Energy Systems (AWES) aim to decrease both the intermittency and cost of wind energy by flying tethered aircraft, called *kites*, higher than conventional wind turbines, in *cross-wind* manoeuvres designed to maximize the kite's apparent velocity. Typically, AWES generate power either in *lift-mode* with *pumping cycle* trajectories that wind and unwind a ground-station generator, or in *drag-mode* with onboard power production. (Loyd, 1980)

For single-kite AWES, tether drag can be significant, as the top of the tether perceives the same high apparent velocities as the kite. This is unfortunate, as the total available power for an AWES is inversely proportional to the square of the system drag. A *Multiple-kite AWES* (MAWES) (see Figure 1) reduces tether drag over a single-kite AWES by splitting the main tether into two or more secondary tethers, each holding an equivalent kite. As the main tether does not travel cross-wind, the total tether drag for a MAWES is less than for a single-kite AWES.

Like all wind energy systems, MAWES convert the flow kinetic energy into electrical energy. The kinetic energy decrease of an incompressible fluid occurs gradually, such that the flow arrives at the kite location with a slower velocity than the free-stream. This phenomenon, called *induction*, decreases the available energy within the flow

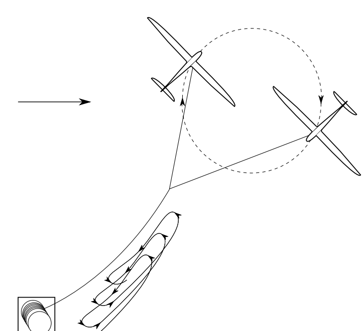

Fig. 1. A sketch of a two-kite ($N = 2$) MAWES

along the *axial*, *angular*, and *radial* coordinates of MAWES kite rotation. For model parsimony in optimal design and control of MAWES, it should be determined whether induction can be safely neglected in MAWES models.

This is not a trivial question, given that induction has widely different levels of influence in similar systems. For single-kite drag-mode AWES, Vander Lind (2014) reports that induction has no practical effect because crosswind velocity dominates the kite's apparent velocity. As a result, current studies of MAWES (Houska and Diehl, 2007; Zanon et al., 2013) typically neglect induction. However, induction is well established to have a large impact (Manwell et al., 2009) on horizontal axis wind turbines. Further, Zanon et al. (2014) estimates that axial induction can decrease available power in a two-kite drag-mode MAWES by 39 percent.

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As far as the authors are aware, induction effects in MAWES of more than two kites, especially considering angular induction and lift-mode power generation, have not yet been studied. Consequently, the purpose of this work is to assess whether it is necessary to include axial and angular induction in the modelling of a lift-mode MAWES with two or more kites. Radial induction is outside the scope of this analysis.

The approach chosen here is to maximize the power output of a highly-idealized lift-mode MAWES, and consider whether induction strongly changes the optimization result, in terms of performance and design. Induction effects can be modelled using the Blade-Element Momentum method (BEM) (Manwell et al., 2009), to include either *No Induction* (NI), *only Axial Induction* (AI) or *Axial and Angular induction* (AA), by selectively requiring that the net downwind force and torque equal the flow downwind momentum change.

2. ASSUMPTIONS FOR A HIGHLY-IDEALIZED MAWES PROBLEM

Under certain assumptions, the MAWES problem simplifies significantly into a highly-idealized MAWES problem. First, for cross-wind flight at large angular velocities, gravitational forces may be negligible in the face of kite centrifugal and aerodynamic forces. Second, the wind shear may be negligible, if the secondary tethers are much shorter than the main tether. By also neglecting atmospheric turbulence, the free-stream wind field is rendered approximately uniform. Further, when the gravitational and drag force on the main tether are much smaller than the total force acting on the system, the main tether might be neglected entirely.

Under these assumptions, the MAWES problem becomes axisymmetric and rotationally-steady about the free-stream wind direction. Then, an analysis of one kite-and-secondary-tether describes the entire MAWES. Rotational-steadiness requires that the forces from this kite-and-tether be parallel to the secondary tether. However, as the tethers are modelled rigidly and the forces acting on the kite-and-secondary tether are not applied at the same location, the torque from the modelled forces may be nonzero. To ensure that the net torque is still zero and satisfies rotational-steadiness, it is assumed that there is a balancing pure-moment acting at the tether connection point.

The kite of the single kite-and-secondary-tether within this static problem is approximated as a thin, symmetric, and elliptical wing, with some mean aerodynamic chord c, span b, and mass m. As it is assumed that there is a vertical stabilizer to generate restoring yaw momentum, the elliptical wing is oriented not to experience side-slip. Additionally, the angle-of-attack (AoA) must be small such that the flow remains attached. The secondary tether is assumed to be straight - without sag or strain, and with a uniform diameter ϕ and density ρ_T - and attached to the kite's center of gravity.

Then, a MAWES can be highly-idealized (see Figure 2) as a N-symmetric system, using a symmetric coordinate system with axial $\hat{\boldsymbol{x}}$, tangential $\hat{\boldsymbol{y}}$, and radial $\hat{\boldsymbol{z}}$ basis vectors. The kite is oriented with chord-wise $\hat{\boldsymbol{e}}_1$, span-wise $\hat{\boldsymbol{e}}_2$, and up $\hat{\boldsymbol{e}}_3$ basis vectors.

The problem is non-dimensionalized for design-point comparison and numerical conditioning. Non-dimensionalization is indicated with a "tilde" such that the free-stream velocity vector $\boldsymbol{U}_\infty = U_\infty \hat{\boldsymbol{x}}$ can be described as $\widetilde{\mathbf{U}}_\infty = \hat{\boldsymbol{x}}$.

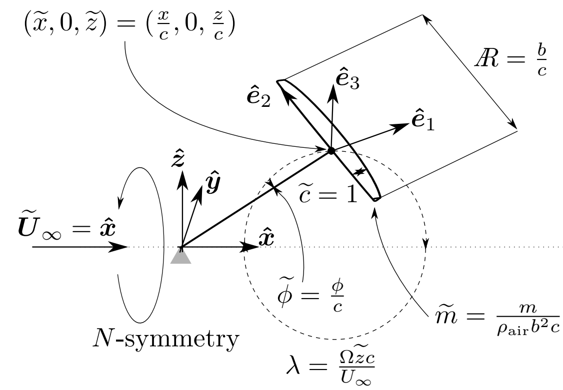

Fig. 2. Parameters in a highly-idealized MAWES

The equivalent kite has its center of gravity at $(\widetilde{x}, 0, \widetilde{z}) = (x/c, 0, z/c)$ and is described by a normalized mean aerodynamic chord $\widetilde{c} = 1$, aspect ratio $AR = b/c$, and tether diameter ratio $\widetilde{\phi} = \phi/c$. To prevent collisions, it is assumed that $\widetilde{z}$ must be greater than or equal to half of the aspect ratio AR:

$$\widetilde{z} - \tfrac{1}{2} AR \geq 0. \tag{1}$$

The mass of the kite is described by a mass-ratio $\widetilde{m} = m/(\rho_{\mathrm{air}} b^2 c)$ that increases with both the planform area and the span, due to additional internal stiffening. The angular velocity Ω sets the tip-speed-ratio $\lambda = \Omega \widetilde{z} c / U_\infty$; the reel-out velocity $f U_\infty \hat{\boldsymbol{x}}$ sets the reel-out factor f.

3. THE BLADE-ELEMENT MOMENTUM METHOD

The BEM can be applied to the above idealized MAWES, beginning with a definition of the axial a and angular a' induction factors:

$$a = 1 - \widetilde{u}_{\mathrm{w}} = 1 - \frac{u_{\mathrm{w}}}{U_\infty}, \tag{2}$$

$$a' = \frac{\widetilde{v}_{\mathrm{w}}}{\lambda} = \frac{1}{\lambda} \frac{v_{\mathrm{w}}}{U_\infty} = \frac{\omega}{\Omega}, \tag{3}$$

where the flow velocity at the kite location is considered to be $\boldsymbol{u}_{\mathrm{w}} = u_{\mathrm{w}} \hat{\boldsymbol{x}} + v_{\mathrm{w}} \hat{\boldsymbol{y}} = U_\infty (\widetilde{u}_{\mathrm{w}} \hat{\boldsymbol{x}} + \widetilde{v}_{\mathrm{w}} \hat{\boldsymbol{y}})$, and ω is the angular induced velocity.

In BEM, thrust and torque expressions are implicit functions of the two induction factors. The thrust can be non-dimensionalized by the free-stream dynamic pressure $q_\infty = \frac{1}{2} \rho_{\mathrm{air}} U_\infty^2$, and the kite planform area $S = bc$. The torque is additionally non-dimensionalized by the mean aerodynamic chord c:

$$\widetilde{T} = \frac{T}{q_\infty S} = N \, \frac{\boldsymbol{F} \cdot \hat{\boldsymbol{x}}}{q_\infty S} = N \, \widetilde{\mathbf{F}} \cdot \hat{\boldsymbol{x}}, \tag{4}$$

$$\widetilde{Q} = \frac{Q}{q_\infty S c} = N \, \frac{\boldsymbol{Q} \cdot (-\hat{\boldsymbol{x}})}{q_\infty S c} = N \, \widetilde{\mathbf{Q}} \cdot (-\hat{\boldsymbol{x}}), \tag{5}$$