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Multi-mass dynamic model of a variable-length tether used in a high altitude wind energy system

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ABSTRACT

This paper presents a multibody approach to dynamics modelling of a variable-length tether moving through air, in a system where an airborne module generates aerodynamic lift and uses the tether to cyclically drive the winch-generator unit fixed on the ground. The rope is modelled as a series of straight, massless, elastic segments with the rope mass fragments lumped to the segment joints. Individual segment length is constant, with the exception of segment being wound out from the winch, while the number of segments is variable. For the segment being wound out, a special modelling approach is derived. The forces acting on the rope are also concentrated at the joints, thus simplifying computations and facilitating rope aerodynamic drag modelling. The proposed tether dynamics model is integrated into the overall model of controlled power production system and verified by computer simulation. The model is compared with two simpler tether dynamics models also proposed in the paper.

1. Introduction

A number of airborne module-based wind energy concepts have been proposed within the last decade, motivated by the ground-based wind turbine systems nearing their technological limits, and also suffering from the intermittent nature and relatively low speed/power of near-surface winds. For instance, the ascending–descending kite-based “Laddermill” system is analysed in [1], where the generator is fixed on the ground. The analysis of another kite-based system, “Kite-Gen”, used in a carousel-like arrangement, is given in [2]. Stationary tethered rotorcraft systems, that use flying electric generators, are discussed in [3]. A lighter-than-air stationary system that also uses a flying electric generator is presented in [4].

The particular high-altitude wind energy (HAWE) system [5], considered in this paper, consists of an airborne module (ABM) connected by a tether to the winch-generator ground station unit (Fig. 1a), as opposed to the conventional wind turbines connected directly to the generator, whose design aspects are overviewed in [6]. Strong and relatively steady high-altitude wind (as assessed in [7]) produces the aerodynamic lift by inducing the Magnus effect on a rotating cylindrical balloon of the ABM, thereby driving the generator during the ABM ascending phase. The same electrical machine is used as a motor during the ABM descending phase, when the cylinder rotation speed is kept close to zero. Previously conducted theoretical studies [5] and preliminary field test results have shown that the energy production based on the described concept is viable. In order to smooth the inherently intermittent power production response of this system during a single operating cycle (Fig. 1b), the ground station mechatronics unit should include an electric storage subsystem [8]. The storage subsystem stores the generated energy during the ascending phase, and delivers it to the generator and the grid during the descending phase, thus providing steady grid power over the whole operating cycle.

One of the main development tasks is to design a control system that will maximize the energy production of the cycle (see [9] for more details). An important step towards fulfilling this objective is to derive a control-oriented model of the ABM dynamics, which would be used in various control system design, optimization, and verification studies. An important submodel of the ABM dynamics model is the model of the variable-length tethering rope that connects the ABM and the generator. The rope is a crucial element of the overall energy conversion system, as it both transfers the mechanical power from the ABM to the generator and supplies the balloon motor with electricity. This paper proposes several rope dynamics models developed for the ABM planar (2D) motion. These models can also be used in other applications where the rope dynamics is concerned (see e.g. [10]).

The static rope models such as the catenary rope model [11] are suitable for quasi-static analyses, where forces at the rope ends are

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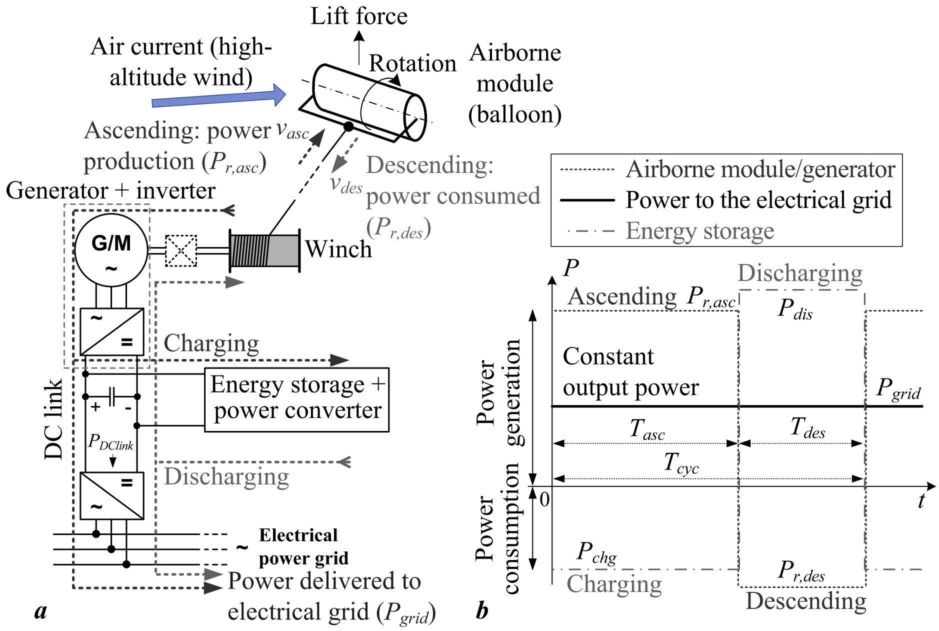

Fig. 1. Schematic of the HAWE system (a) and illustration of its idealized power cycle (b).

derived by assuming rope static equilibrium in successive instants during rope unwinding (or winding). Although those models can reflect the effect of variable rope length, they do not capture the effects related to rope inertia and compliance. In addition, such models treat the rope as a single body, making it difficult to account for the aerodynamic forces caused by the wind, especially when the wind speed changes with height. It is thus advantageous to derive a multi-mass rope model, where the rope is modelled as a series of straight, massless, elastic segments, with rope mass lumped to segment joints. The development of such model, which is preceded by its simpler versions (e.g. with one concentrated/central rope mass), is the main objective and novelty of this paper.

The proposed model differs from similar dynamic rope models (see e.g. [12]) in that the segments are not rigid, and the number of unwound segments with their lumped masses is not constant. Conversely, lengths and masses of unwound segments *are* constant. The only exception is the segment that is being wound out, for which a special submodel is derived including a proper algorithm for "launching" this segment from the winch.

The proposed multi-mass model is verified by means of computer simulations and compared with the simpler models.

2. Basic models of airborne module and winch dynamics

The rope submodel model is a part of an overall HAWE system dynamics model, where it links the 2D ABM dynamics model (described in [5,9]) and the winch dynamics model. Its outputs include (i) the ABM-side rope force F_r as an input of the ABM dynamics model and (ii) the winch-side rope force $F_{r,w}$ supplied to the winch dynamics model.

The ABM dynamics model is briefly overviewed using the illustration of the system planar dynamics shown in Fig. 2. The forces acting on the ABM include: the aerodynamic drag force F_d, the aerodynamic lift force F_l, the buoyancy force F_b, the ABM weight force F_g, and the ABM-side rope force F_r. The force components are considered positive when oriented as in Fig. 2, and negative for opposite orientation. The aerodynamic forces are calculated from the relative velocity between the air and the ABM, $\vec{v}_{rel} = \vec{v}_w - \vec{v}$. The reference direction of the cylinder angular velocity ω_{cyl} is chosen so that for the shown reference direction

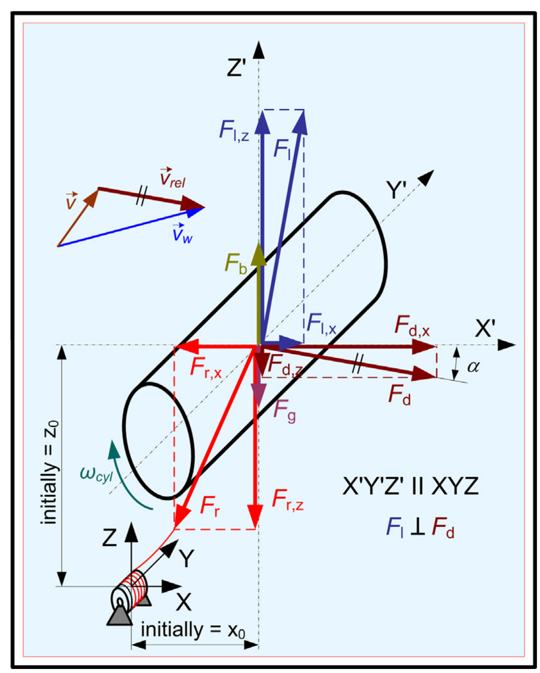

Fig. 2. Reference coordinate system, forces and velocities of the basic two-dimensional ABM dynamics model.

of the wind velocity $\vec{v}_w$, the Magnus effect causes a lift force F_l that points upward (i.e. that has a positive z component). With ABM mass denoted as m_{ABM}, the ABM dynamics equations are:

$$\dot{x} = v_x \tag{1}$$

$$\dot{z} = v_z \tag{2}$$

$$\dot{v}_x = \frac{F_{d,x} + F_{l,x} - F_{r,x}}{m_{ABM}} = \frac{F_{tot-r,x} - F_{r,x}}{m_{ABM}} \tag{3}$$

$$\dot{v}_z = \frac{F_{l,z} - F_{d,z} - F_{r,z} + F_b - F_g}{m_{ABM}} = \frac{F_{tot-r,z} - F_{r,z}}{m_{ABM}} \tag{4}$$