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Modeling and Control of a Magnus Effect Kite: Pumping Cycle with Reversing Rotation

Introduction

Wind Fisher is developing an airborne wind energy system based on an innovative dual-cylinder Magnus effect kite. The system utilizes cross-wind flight and optimizes wing lift and drag during reel-in and reel-out phases. Developing a simulator enables to test control strategies to ensure prototype stability during our flight test and also to simulate and estimate the pumping cycle energy production of the future 100kW to MW scale systems. The model includes two cylinders with a rigid structure, two tethers and four drive-train units connected to each end of the tethers.

Modeling the magnus effect kite

In order to test piloting algorithms and also simulate the pumping cycle energy production, we extended our 2D model [1] to a comprehensive 3D model.

The system includes the following elements:

- The magnus effect kite, composed of two rotating cylinders.
- The four winches and motors of the ground station.
- The tethers, wrapped around each cylinder and corresponding winches.

In order to achieve modeling following frames are defined:

- The fixed inertial frame : $R_t\{\boldsymbol{u}_x, \boldsymbol{u}_y, \boldsymbol{u}_z\}$
- The tether frame : $R_c\{\boldsymbol{u}_r, \boldsymbol{u}_\psi, \boldsymbol{u}_\beta\}$ using spherical coordinates (r, ψ, β)
- The structure frame : $R_s\{\boldsymbol{u}_s, \boldsymbol{u}_b, \boldsymbol{u}_{ps}\}$ using angles $(\varphi, \alpha, \gamma)$

An illustration is given in Figure (1).

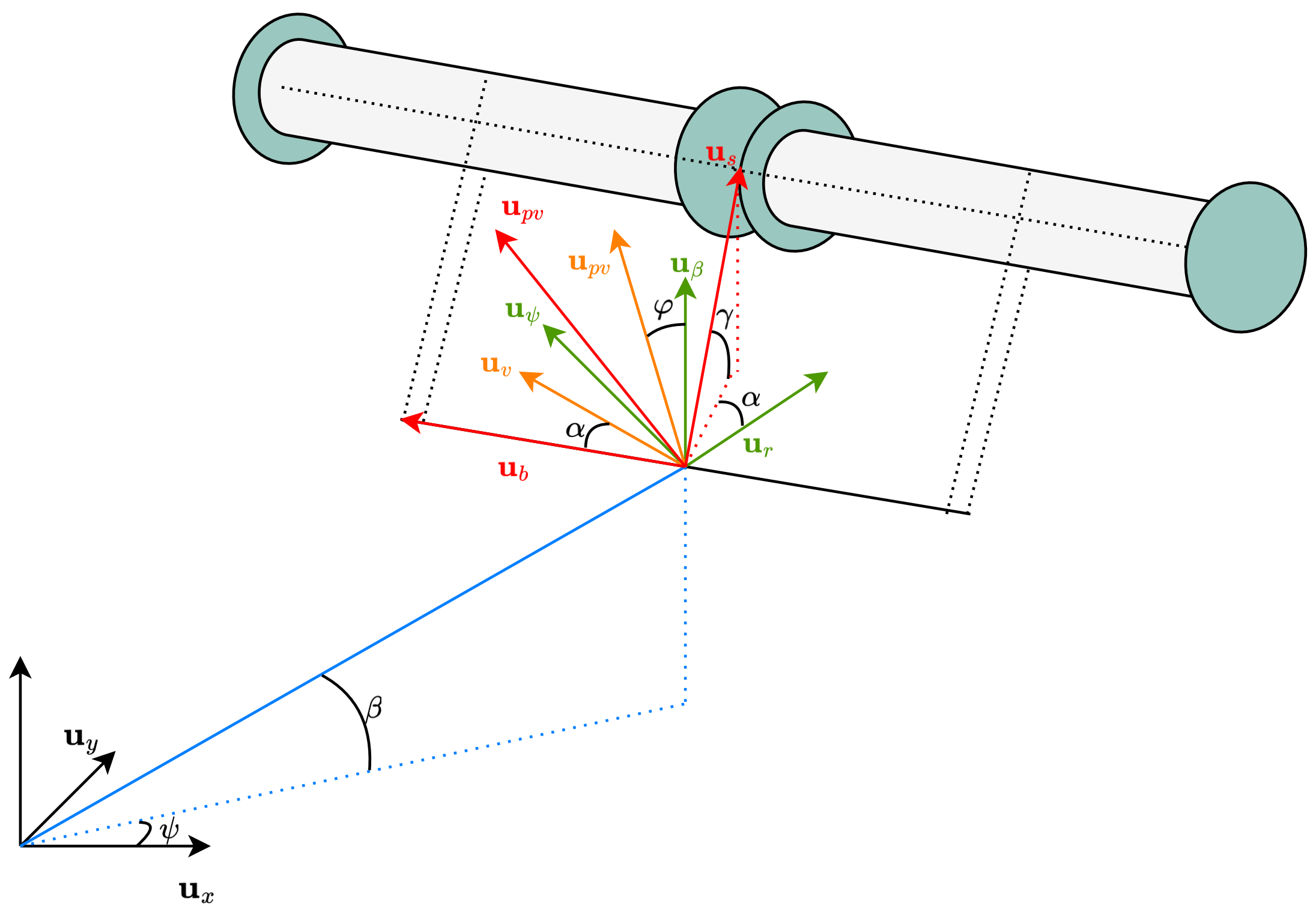

Figure 1: Frames used to model the magnus effect kite

By applying law of physics, the obtained model is a comprehensive model of the form:

$$A(x,u)\,\dot{x} \;=\; B(x,u)$$

using:

$$\begin{aligned} x &= \left[r, \dot{r}, \psi, \dot{\psi}, \beta, \dot{\beta}, \varphi, \dot{\varphi}, \alpha, \dot{\alpha}, \gamma, \dot{\gamma}\right]^T, \\ u &= \left[\Gamma_{\{d,r\}}, \Gamma_{\{d,l\}}, \Gamma_{\{u,r\}}, \Gamma_{\{u,l\}}\right]^T, \end{aligned} \tag{1}$$

where $\Gamma_{\{i,j\}}$ denotes for the four motor torques, $A(x,u)$ and $B(x,u)$ nonlinear functions. B includes the aerodynamic forces and moments using coefficients from *Badalamenti* experimental results [2].

Control architecture

To achieve the pumping cycle energy production, we use a decoupled control architecture to pilot the four motor torques. The complete architecture is given in the following Figure (2).

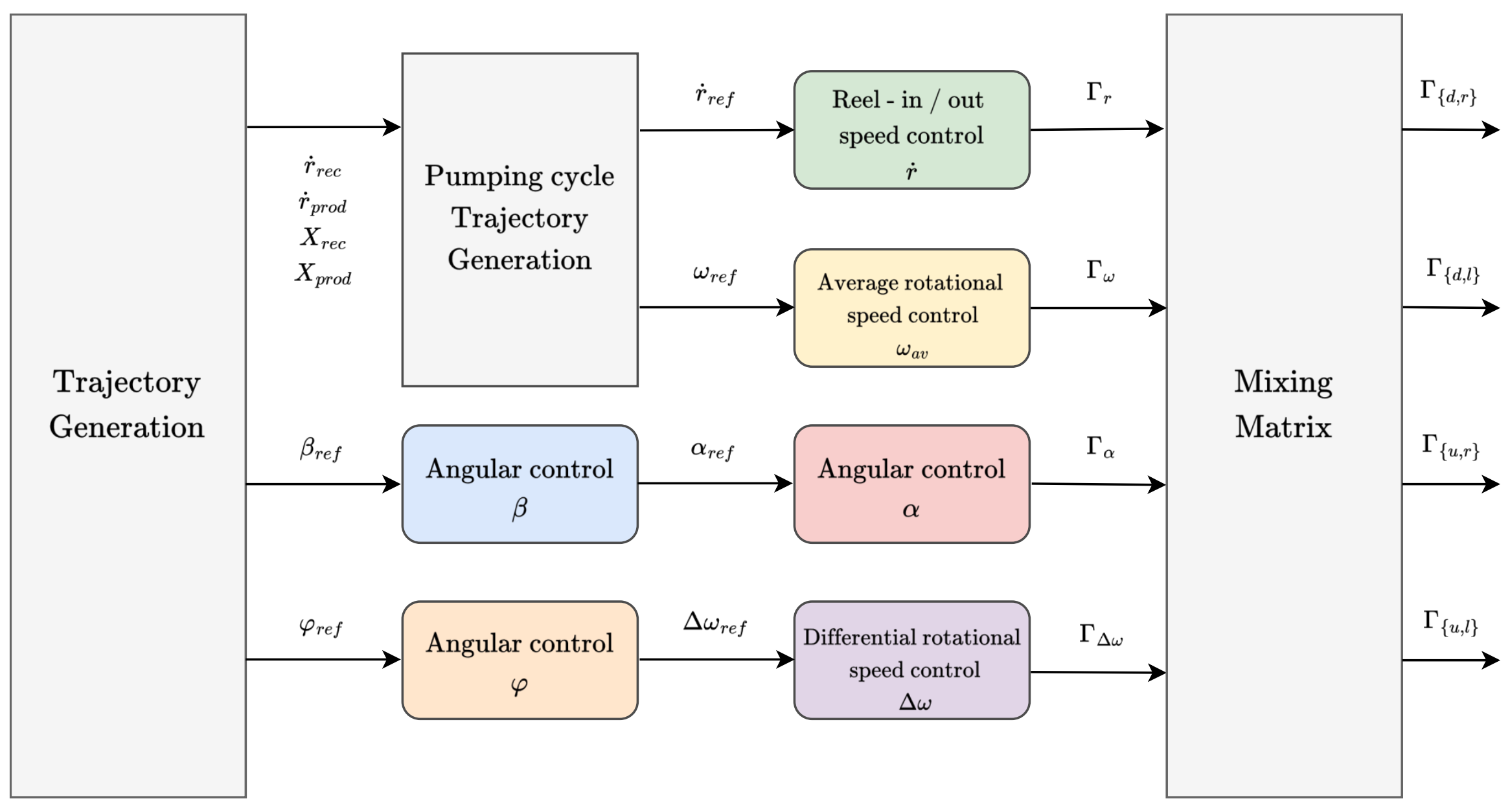

Figure 2: Magnus effect kite control architecture

Pumping cycle

The pumping cycle trajectory generation block manages the reeling speed $\dot{r}$ and the cylinders average rotational speed ω_{av} so as to optimize the energy production of the cycle.

As illustrated in Figure (3), the trajectory consists of a figure-of-eight, whose half-cycle includes:

- First, a reel-out phase until the maximum radius where we pilot ω_{av} to maintain an optimal spin ratio X_{prod} (ratio between cylinders tangential speed and apparent wind speed) and maximize energy production.
- Second, a reel-in phase, as short as possible, to recover the tether where we reduce the spin ratio X_{rec} to minimize the energy consumption.

To complete the full pumping cycle we reverse the rotation of the cylinders, to start again the procedure in the other direction.

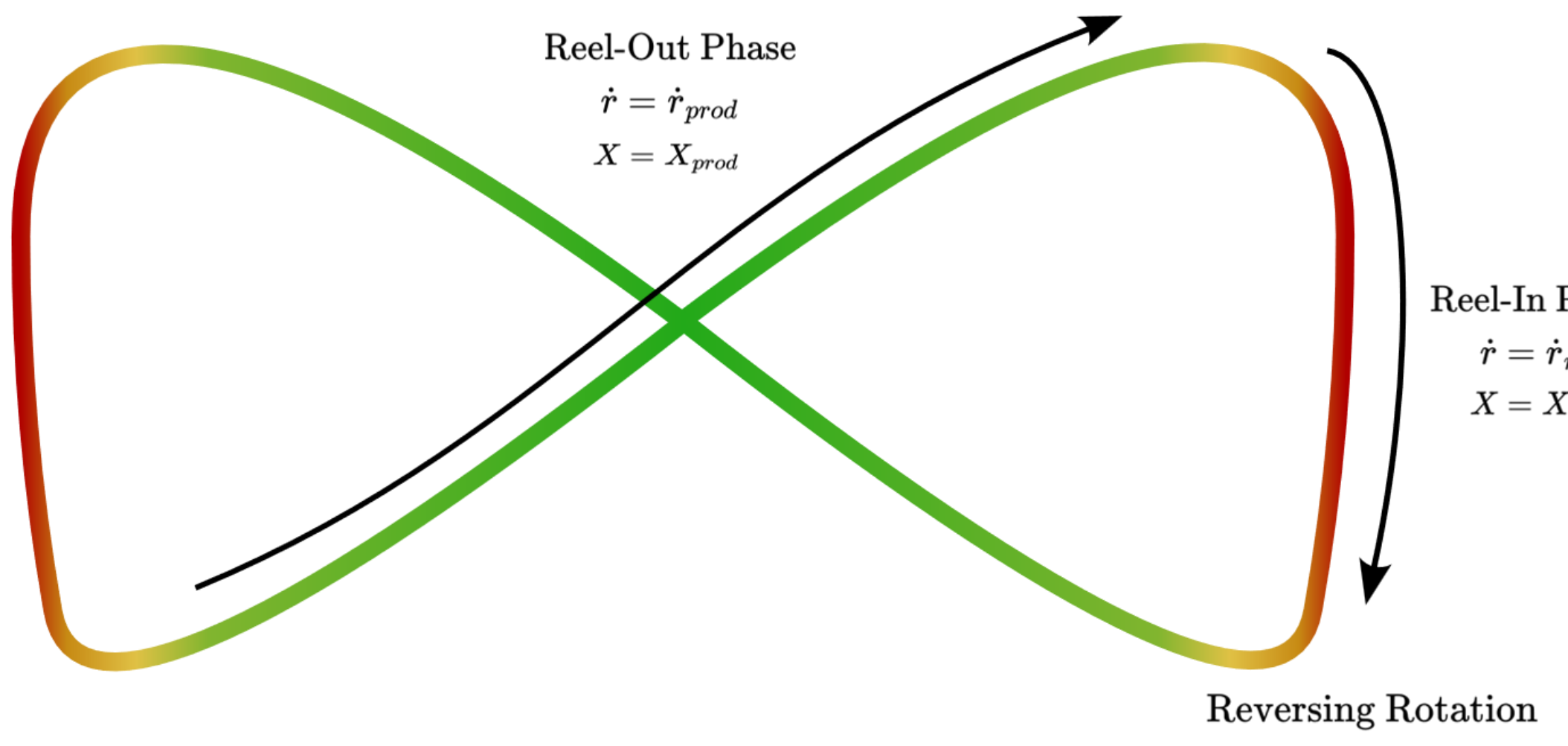

Figure 3: Pumping cycle trajectory generation

For high wind speeds, we reduce aerodynamic forces during the reel-out phase by switching to a non-optimal spin ratio and reel-out speed ($\dot{r}_{\text{prod}}$ & X_{prod}), this allows to limit the tension in the tethers.

Pumping cycle simulation results

Using presented model and control, we are able to simulate pumping cycles and estimate the energy production for different system sizes. Figures (4), (5) & (6), present simulation results of a 100 kW system performing 2 cycles with a wind speed of 8m/s:

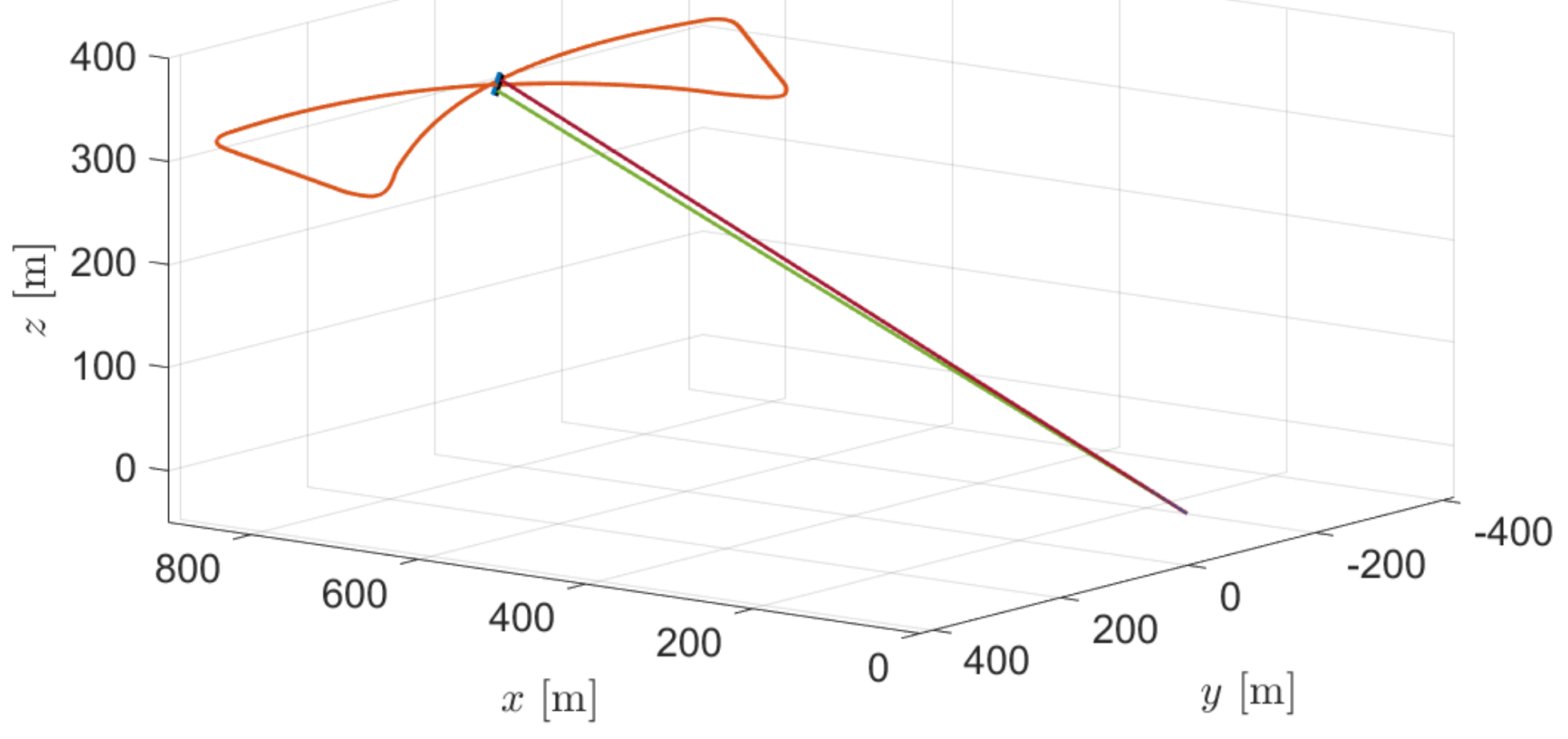

Figure 4: Figure-of-eight flight trajectory

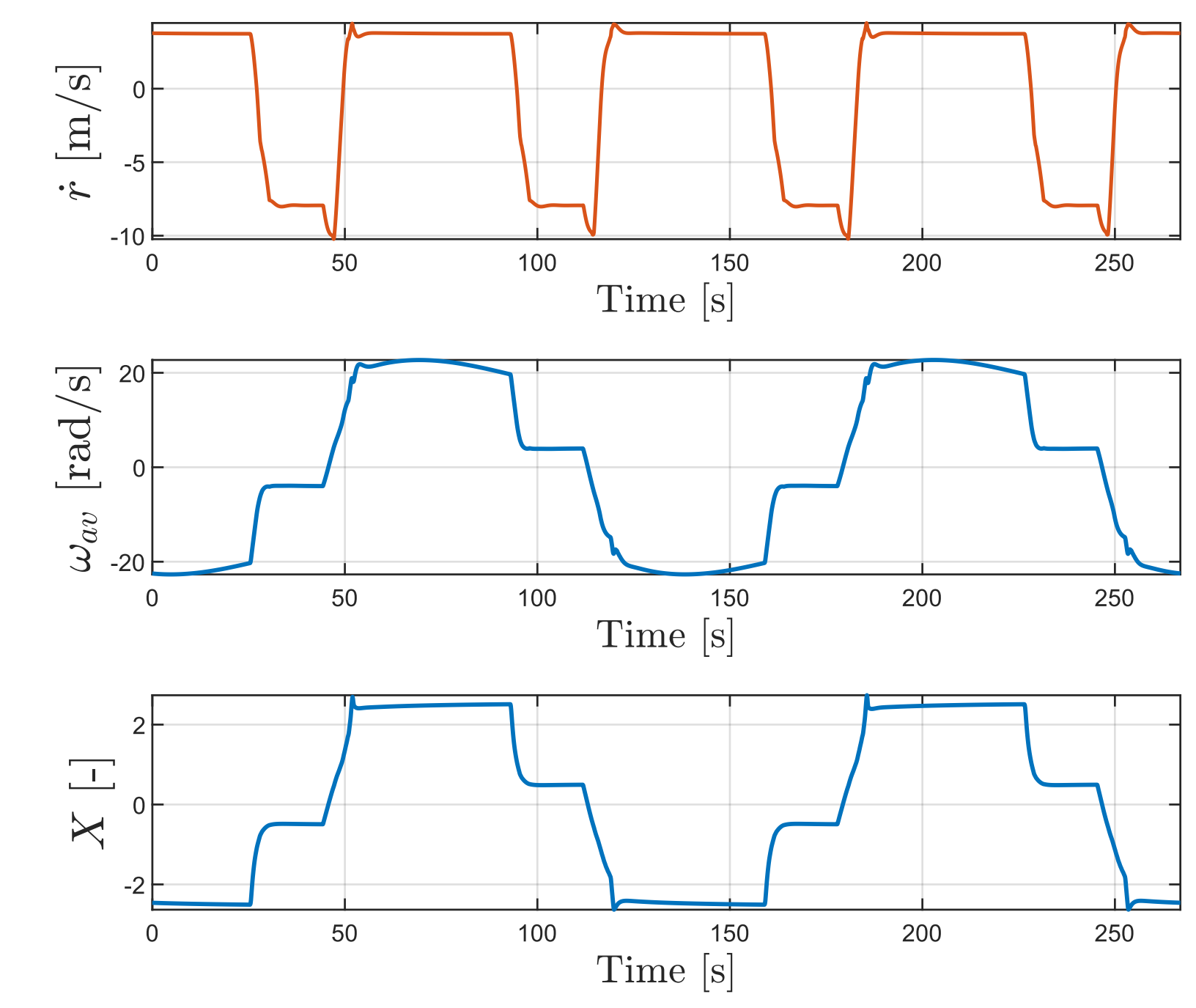

Figure 5: Evolution of reeling speed, cylinders average rotational speed and spin ratio during pumping cycles

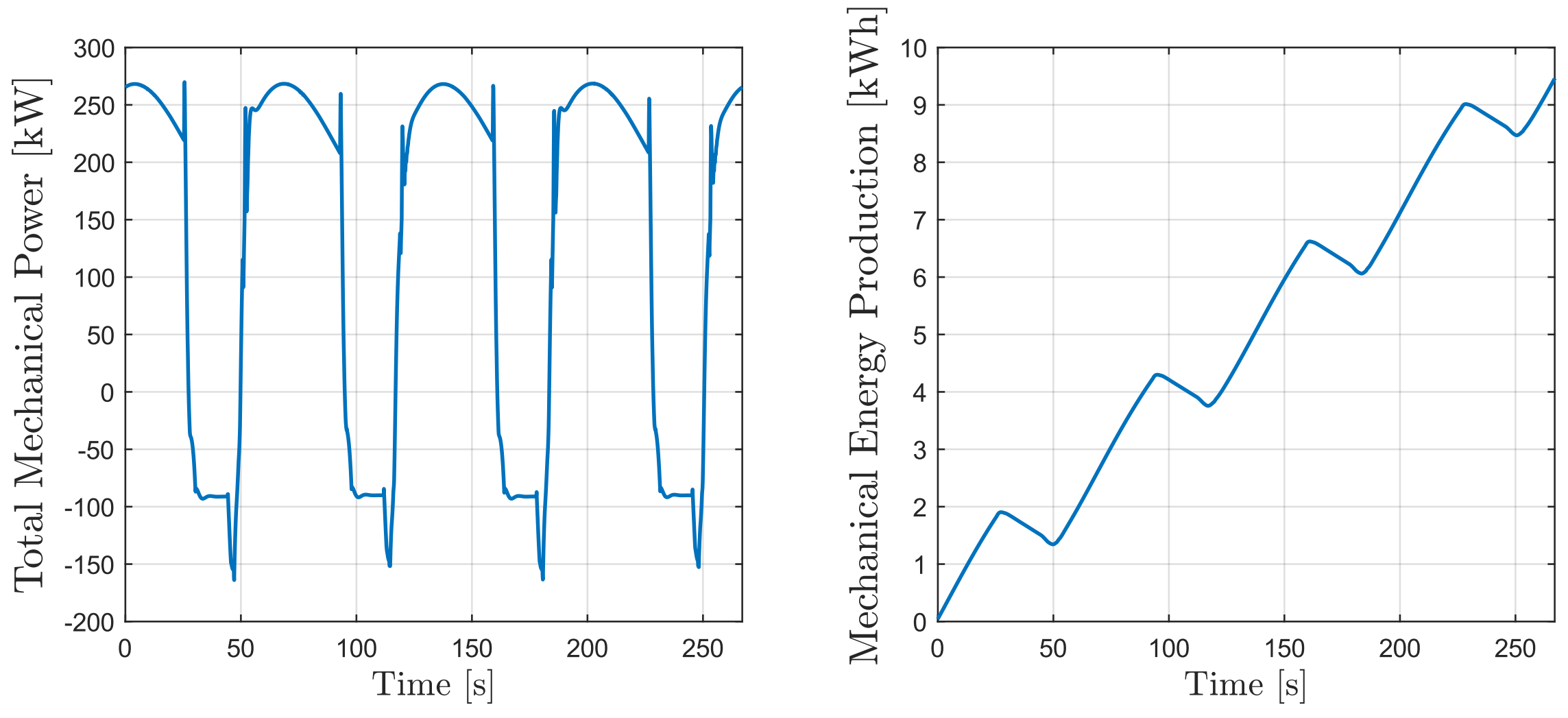

Figure 6: Mechanical power & energy production evolution during pumping cycles

Piloting yaw angle

In order to achieve yaw angle φ control, we use differential rotation to generate torque. The control is designed using a simplified model of (1).

The control architecture is composed of two steps:

- A state feedback using disturbance rejection to pilot the total moment around the cable axis:

$$M_\varphi(t) = -k_p\left(\varphi(t) - \varphi_{ref}(t)\right) - k_d\,\varphi(t) - \hat{d}(t)$$

- An optimization procedure to inverse the nonlinear model between total moment and the differential rotational speed, at each controller step:

$$\begin{aligned} &\min_{\Delta\omega} \left| M_{\boldsymbol{u}_r}(\Delta\omega, t) - M_\varphi(t) \right| \\ &\text{s.t.}\; \Delta\omega_{min} \le \Delta\omega \le \Delta\omega_{max} \end{aligned}$$

To test the proposed strategy, one uses the comprehensive model (1) and a 3D variable wind model. The simulation results are given in Figure (7).

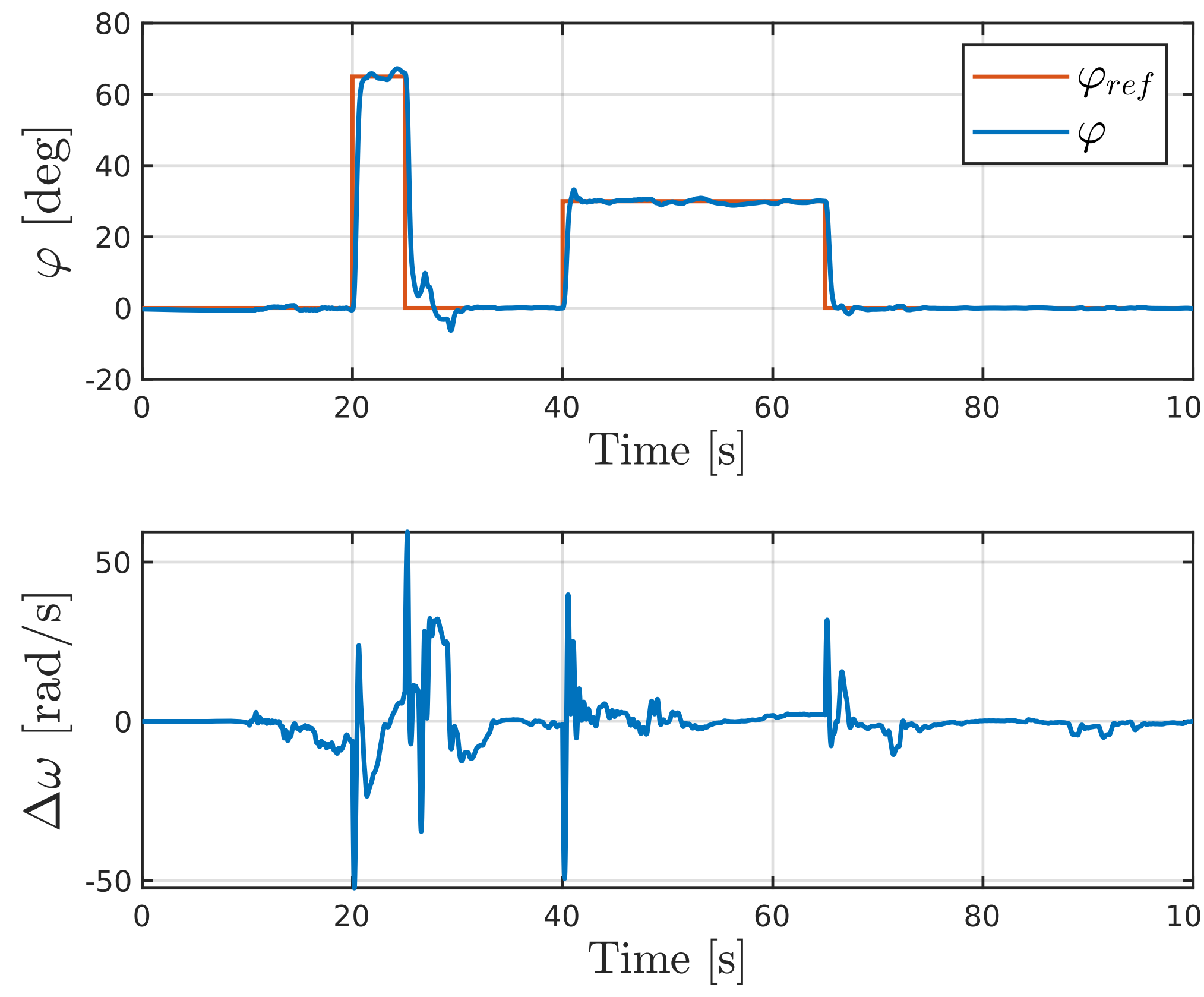

Figure 7: Yaw angle control using proposed strategy

According to Figure (7), the proposed control is able to pilot the yaw at a given reference. We ensured that the optimization problem is solved within the control time interval.

Experimental results

In order to validate first algorithms, we tested our current prototype of the kite in outdoor towed flight tests. Figure (8) demonstrates promising results on take-off and yaw stabilization but with oscillations which requiring further refinement.

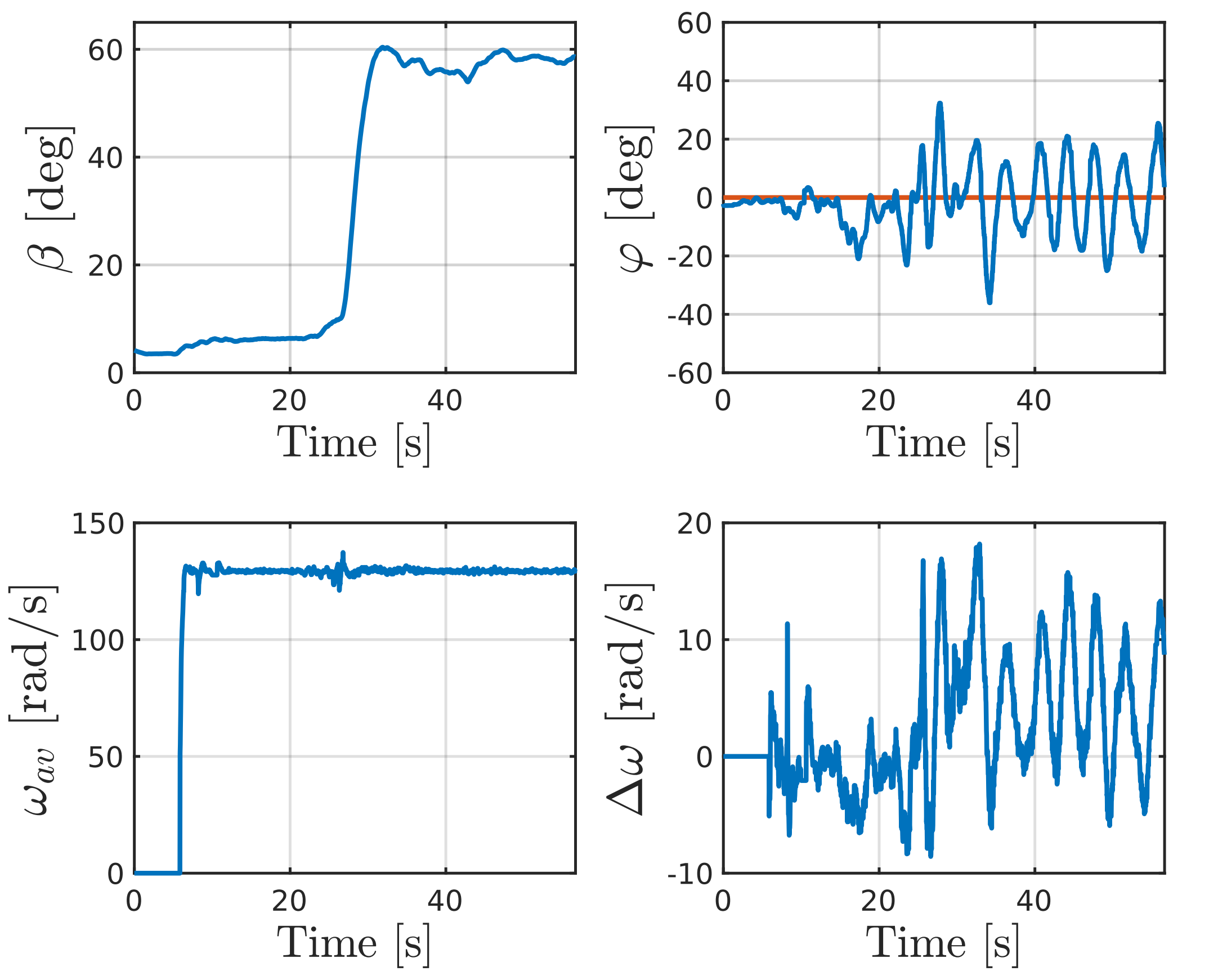

Figure 8: Experimental towed flight results

Perspectives

Concerning control, we are working on improving it to deal with the four-drive train system using advanced methods such as model predictive control.

We are also currently working on improving our prototype, by including the four drive trains, adding new sensors (pitot tube, force sensors, etc.) and increasing mechanical robustness.

Acknowledgements

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References

[1] Smith, G., Tardella, A., Boucheriguene, Y.: Magnus Effect Kites: Optimal Reel-Out Speeds for Cross-Wind Power Production Including Simulation and Test Results. Airborne Wind Energy Conference (AWEC 2021), Milan, 2022.
[2] Badalamenti, C.: On the Application of Rotating Cylinders to Micro Air Vehicles, PhD Thesis, City University London, 2010.

Supported by: