Cyclic Pitch Control of a Rotary Kite

Master's Thesis Presentation

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Airborne Wind Energy

- Airborne Wind Energy (AWE): airborne device in the wind field
- different working principles
  - reel in / reel out
  - onboard generation

Figure: AWE System(Makani Technologeis)

Rotary Kite AWE

- rotary kite airborne wind energy systems: rotor instead of a kite or wing
- different kinds of working principles and energy transmission
- here: energy transmission by a torsionally stiff structure ($\rightarrow$ torque)

Figure: Rotary Kite AWE System

System Setup

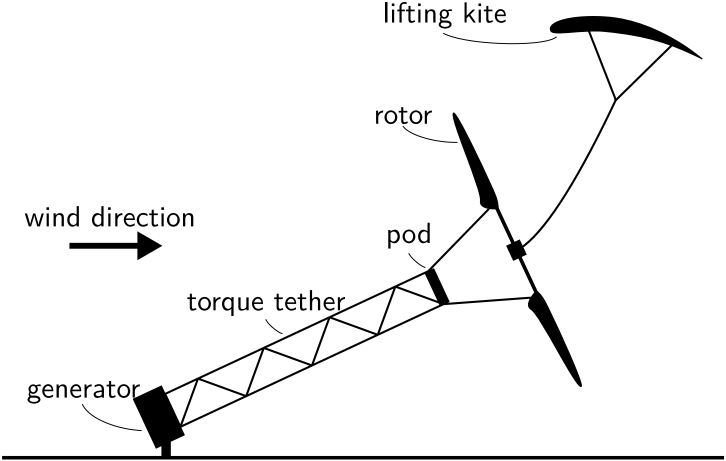

Figure: Overall system setup

Motivation for Removing the Lifting Kite

- no steering possible
- no automated starting and landing
- lifting kite limited to certain wind speeds
- adds complexity
- idea: cyclic pitch mechanism and control
- aim of this thesis:

  investigate this approach for keeping the system airborne

Cyclic Pitch Illustration

- cyclically changing the angle of attack of the rotor blades

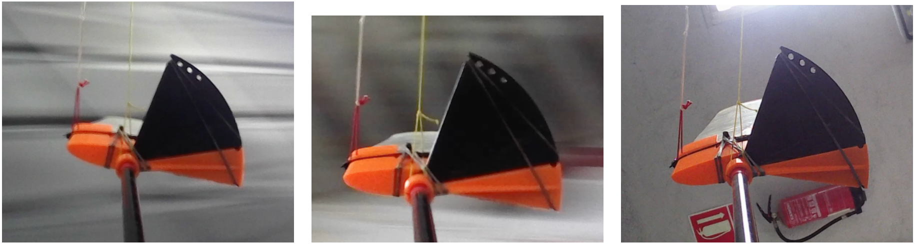

Figure: Cyclic pitch demonstration

Airfoil Aerodynamics

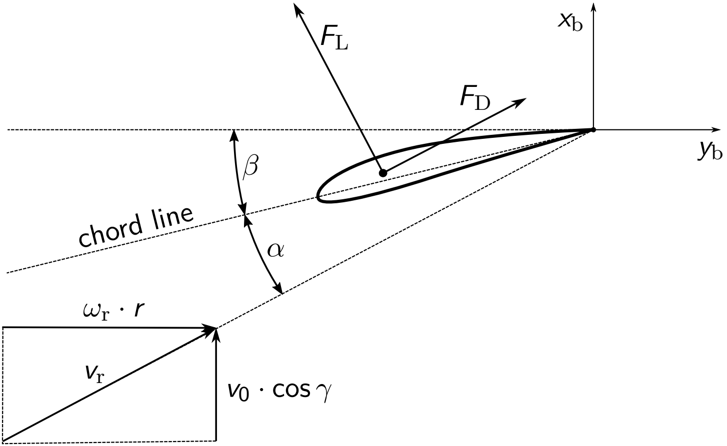

Figure: Forces on the rotor blade

Airfoil Polar

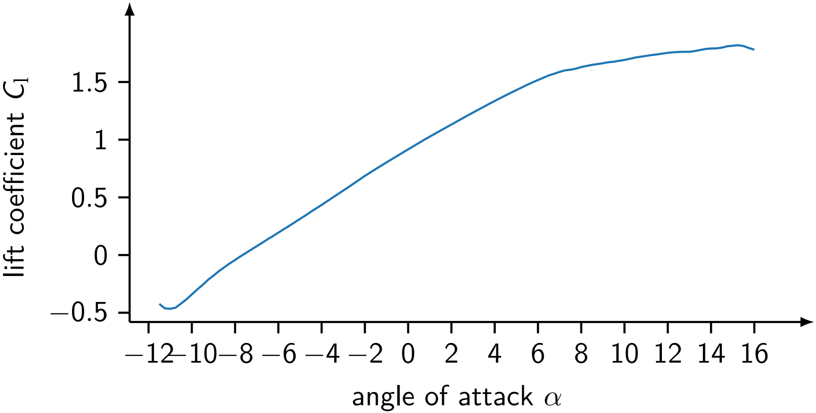

Figure: Polar for the used airfoil

Cyclic Pitch Idea

- cyclic pitch results in a tilting moment on the rotor
- the direction of the overall lift force of the rotor can be adjusted
- this can be used to steer the rotor

Cyclic Pitch Mechanism

- cyclic pitch adjustment using an eccentric mechanism
- stationary part defines eccentric point (→ cyclic pitch amplitude)
- rotation causes a cyclic change of the distance from eccentric point to rotating point
- can be approximated by a sine function
- rotation compensator needed as stationary part (RCD)

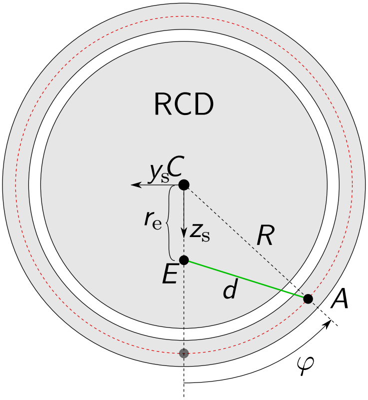

Figure: Eccentric mechanism scheme

Cyclic Pitch Mechanism

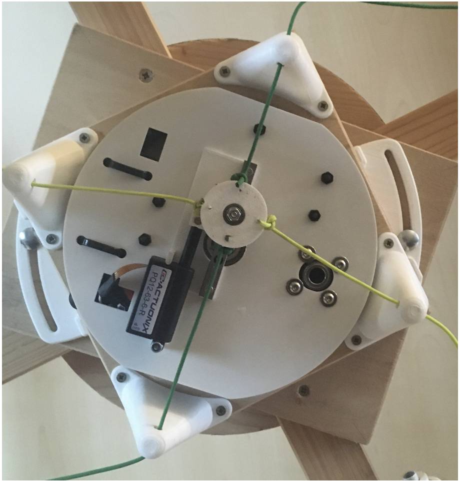

Figure: Cyclic Pitch Scheme

Rotation Compensation

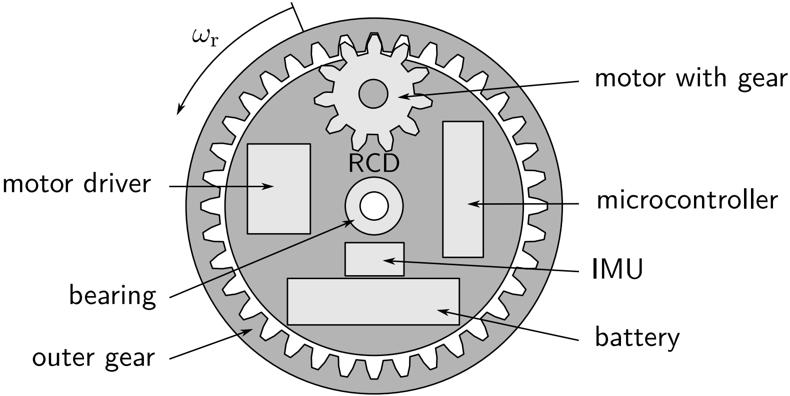

Figure: Active rotation compensation illustration

Blade Pitch

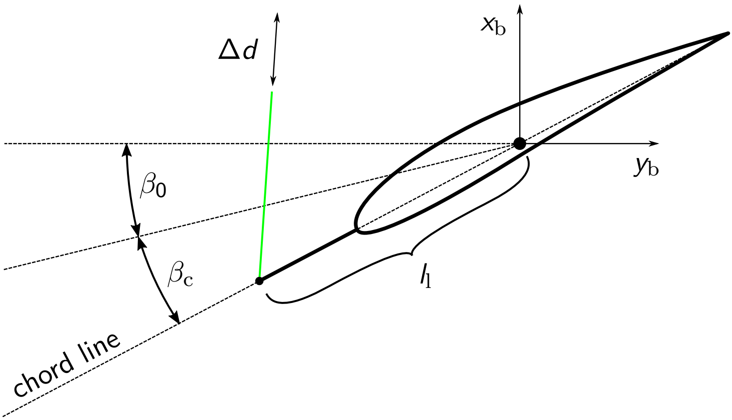

Figure: Blade pitch setup

Modeling Approach

- lift force on the blade depends on the radius
- different modeling strategies possible (BEM, CFD)
- here: experimental approach is taken for modeling
- simple model that reflects the main effects

Control System Overview

- two control loops: rotation compensator and cyclic pitch loop
- rotation compensator as underlying loop
- aim: set the altitude h of the rotary kite

System Overview

$$\mathbf{s} = \begin{bmatrix} h \\ \phi \\ \omega_\mathrm{r} \end{bmatrix} \begin{array}{l} \text{altitude} \\ \text{angle of the rotation comp.} \\ \text{rotor speed} \end{array}$$

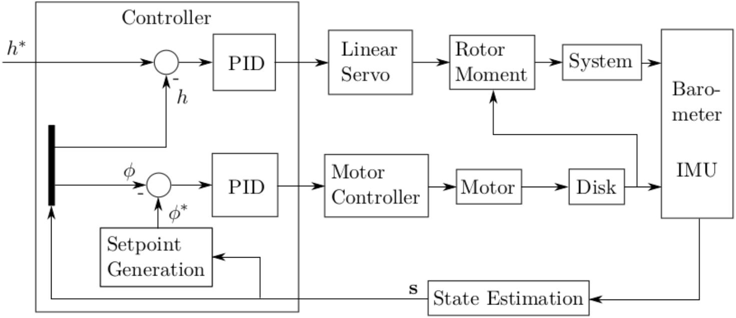

Figure: Control loop overview

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- has been investigated in another thesis using MPC
- is deployed using a simple PID controller due to limitations of the microcontroller
- sensor fusion and state estimation is mainly performed on the IMU itself
- both runs at 50 Hz

Performance

- has been evaluated testing disturbance correction and setpoint following

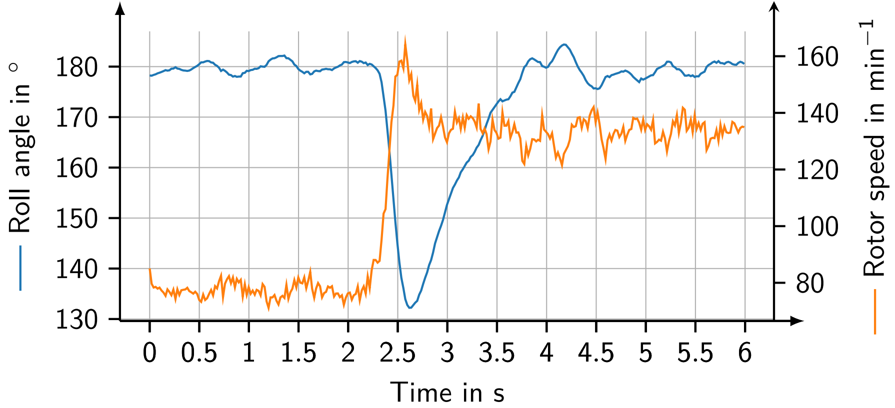

Figure: Jump from 80 min^{-1} to 130 min^{-1}

Performance

- has been evaluated testing disturbance correction and setpoint following

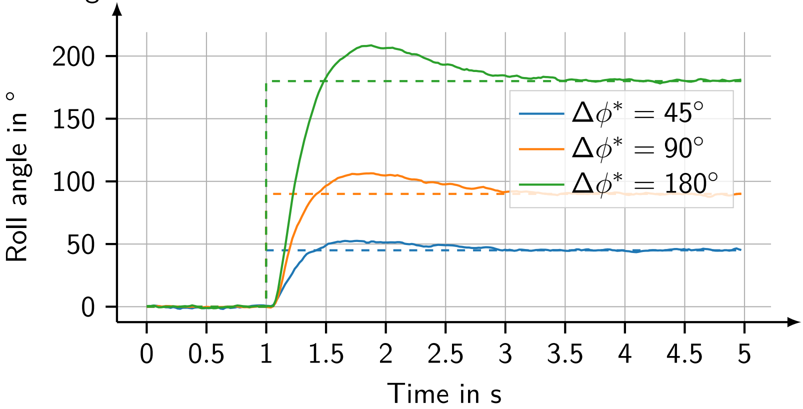

Figure: Setpoint following for different setpoint jumps

Performance

- rotation compensator is able to
  - reach the setpoint
  - correct disturbances
  - follow a setpoint trajectory
- performance might be increased with higher update rate

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Figure: Rotor setup in Alicante

Setup and Methods

- rotor mounted on motor on a wall
- rotor is driven by motor
  - at different speeds
  - for different cyclic pitch amplitudes
  - for different roll angles (rotation compensator)
- force sensors mounted between rotor and motor at each blade rod
- problem: rotating sensors and no IMU on rotor

  $\rightarrow$ deeper data analysis necessary

Experimental Setup

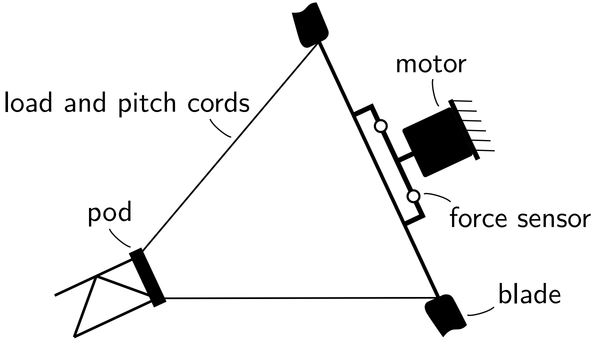


Figure: Experimental rotor setup

Example Data

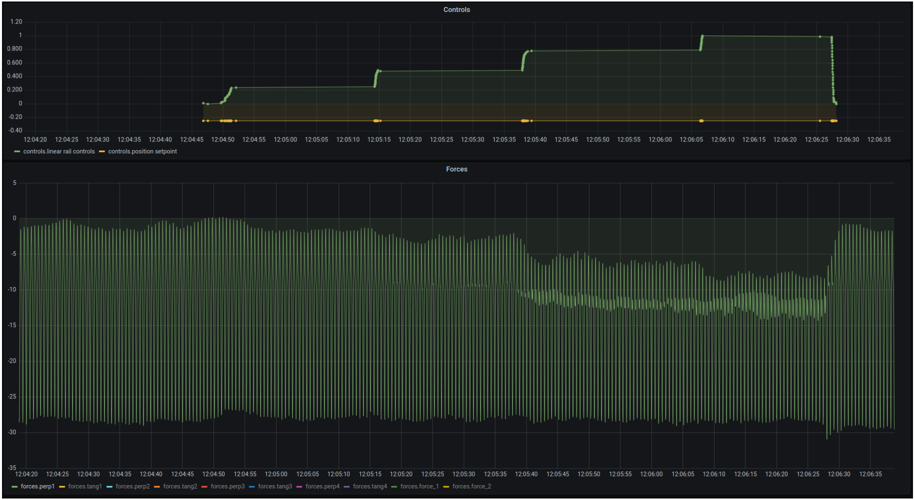
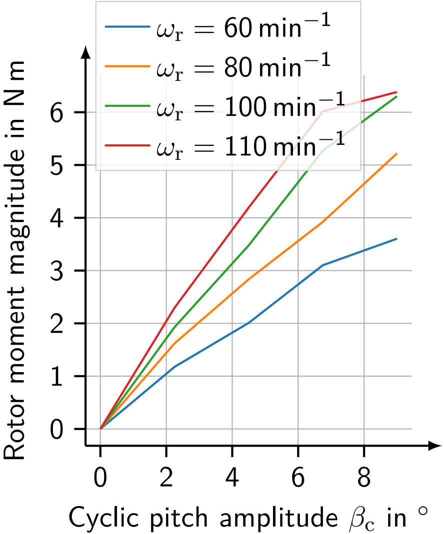
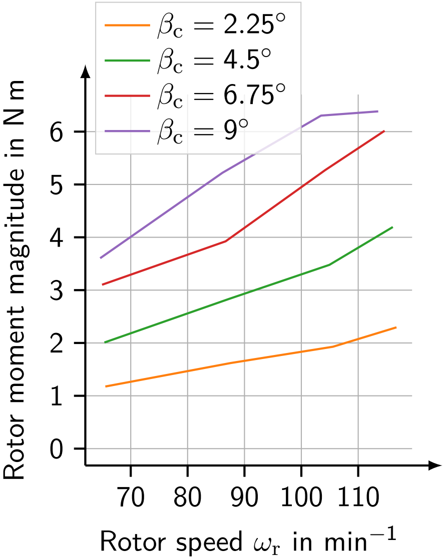


Figure: Data from one force sensor

Results


$\omega_r = 60\,\text{min}^{-1}$
$\omega_r = 80\,\text{min}^{-1}$
$\omega_r = 100\,\text{min}^{-1}$
$\omega_r = 110\,\text{min}^{-1}$
Rotor moment magnitude in N m
0
1
2
3
4
5
6
0
2
4
6
8
Cyclic pitch amplitude β_c in °


$\beta_c = 2.25°$
$\beta_c = 4.5°$
$\beta_c = 6.75°$
$\beta_c = 9°$
Rotor moment magnitude in N m
0
1
2
3
4
5
6
70
80
90
100
110
Rotor speed ω_r in min^{-1}

Results

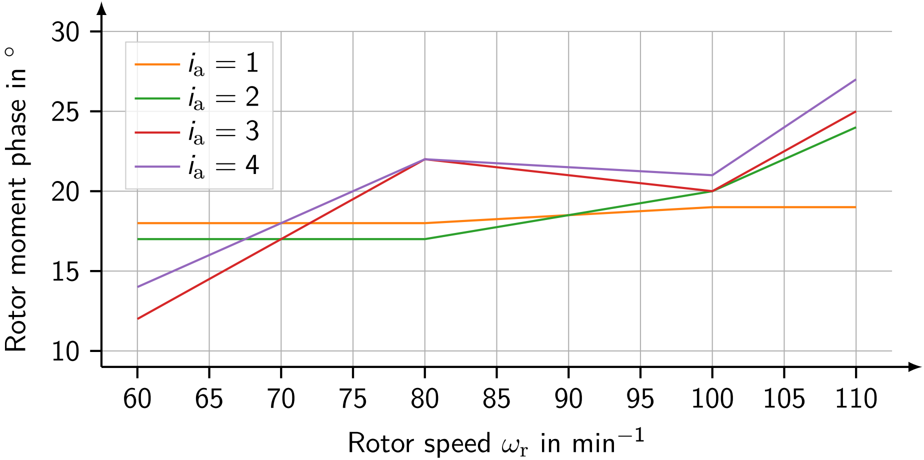


Figure: Phase dependence on rotor speed and cyclic pitch amplitude

Rotor Model

- moment magnitude approximated by an affine map
- moment direction: high uncertainties
- also regard first order effects by an affine map

$$\mathbf{M}^{\mathrm{s}}(\omega_{\mathrm{r}}, \beta_{\mathrm{c}}) = \begin{bmatrix} 0 \\ (c_1 \cdot \beta_{\mathrm{c}} + c_2 \cdot \omega_{\mathrm{r}} + c_3) \cdot \cos(\varphi_{\mathrm{s}}) \\ (c_1 \cdot \beta_{\mathrm{c}} + c_2 \cdot \omega_{\mathrm{r}} + c_3) \cdot \sin(\varphi_{\mathrm{s}}) \end{bmatrix}$$

with

$$\phi_{\mathrm{s}} = c_4 \beta_{\mathrm{c}} + c_5 \omega_{\mathrm{r}} + c_6$$

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Figure: Rotor test rig

Setup and Methods

- uses a different rotor
- force sensors mounted on the axle (do not rotate with the rotor)
  $\rightarrow$ makes data analysis much easier
- also driven by a motor
- rotor moment again measured for different rotor speeds and cyclic pitch amplitudes

Setup scheme

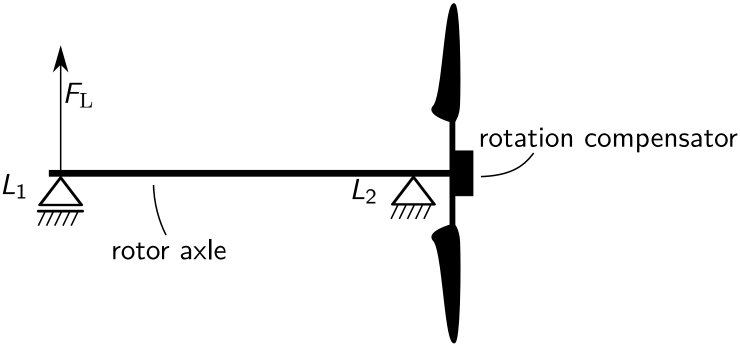

Figure: Setup scheme of the test rig

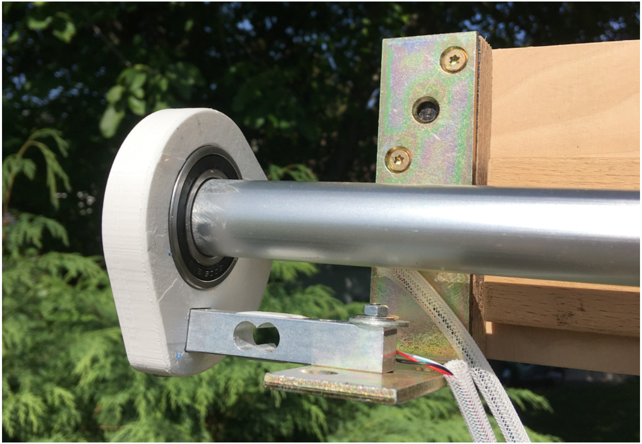

Figure: Force sensor on the test rig

Rotor Model

show video

Results

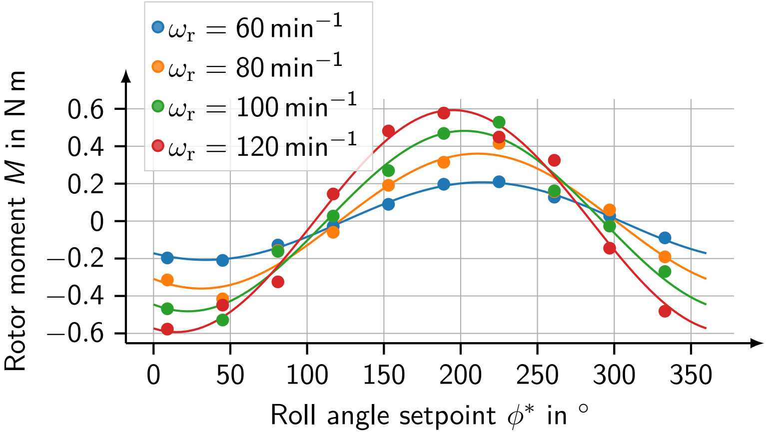

Figure: Rotor moment for different rotor speeds

Results

- support the data of the first experiment
- higher dependence of the direction on rotor speed and pitch amplitude

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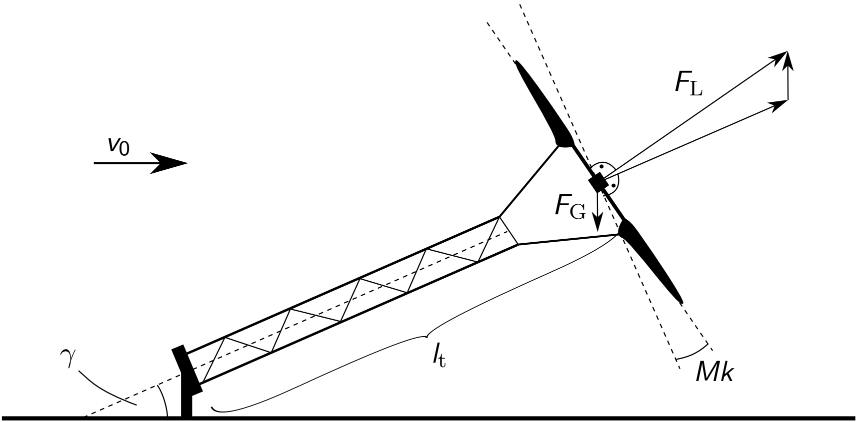


Figure: Simple overall model

- effective area of the rotor decreases with higher elevation angle γ
  $\rightarrow$ lower rotor lift force

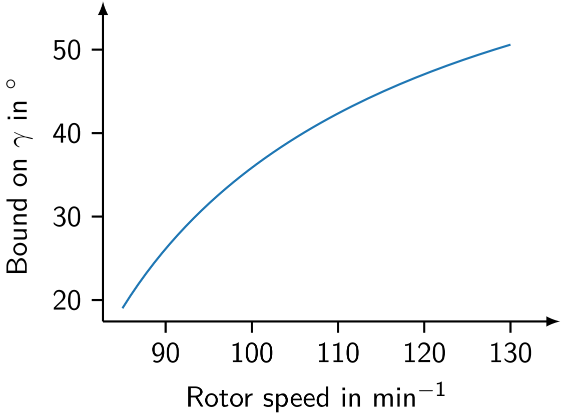


Figure: Upper bound of the elevation angle for a given rotor speed

Simulation

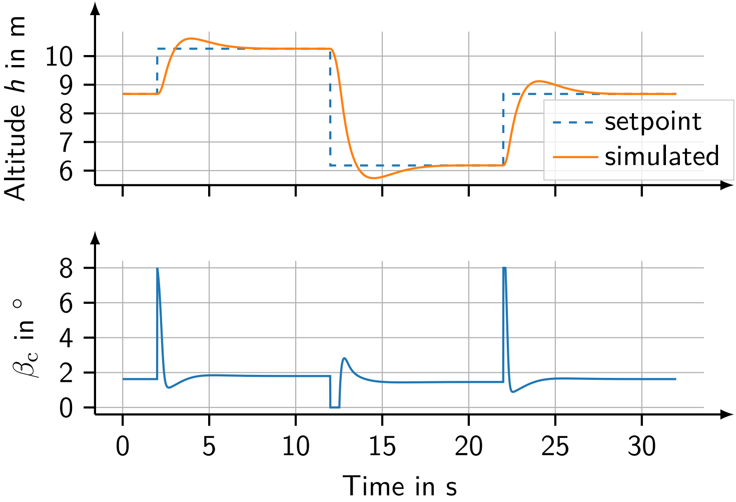
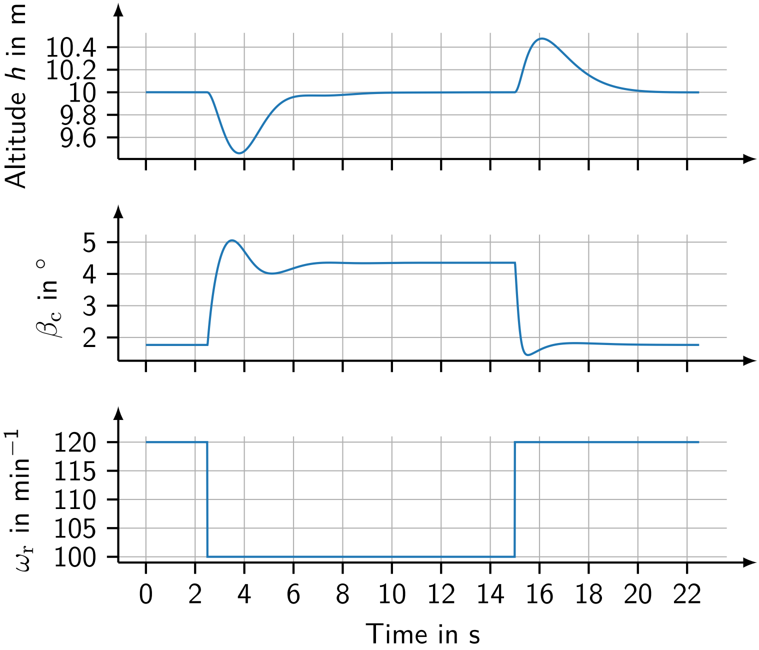


Figure: Simulated system for a setpoint trajectory


Altitude h in m
10.4
10.2
10
9.8
9.6
β_c in °
5
4
3
2
ω_r in min^{-1}
120
115
110
105
100
0 2 4 6 8 10 12 14 16 18 20 22
Time in s

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- aerodynamic rotor model
  - moment magnitude and phase dependence approximated by an affine map
  - only valid for the regarded operating region
  - high uncertainties regarding the phase parameter estimation
- optimization of the rotor needed
  - rotor lift force was assumed as a high theoretical value to make model feasible
- basis for a system model
  - the expected working principle was shown

Thank you for your attention!