Rotational Speed Control of Floating Wind Turbines

January 6, 2023

Martin H. Therkildsen

Control and Automation
Aalborg University
Denmark

AALBORG UNIVERSITY
DENMARK

Agenda

Introduction
Modelling
Controller Design
Test Results
Conclusion

Introduction

Modelling

Controller Design

Test Results

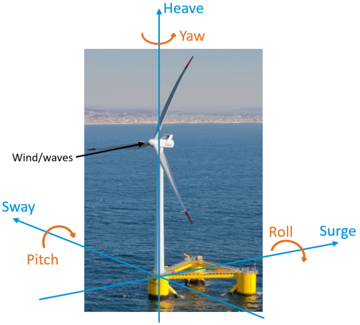
Conclusion

Introduction
State-of-affairs and motivation

- Global energy demand is still rising
- Wind energy is a part of solution to lower CO2 emissions
- LCOE higher in offshore wind turbines but there are advantages
- Shallow-water depth sites (<50 m) will eventually exhaust
- Floating turbines are in prototype stage but maturing
- In recent news: "*Portugal to auction 3-4 GW of floating offshore wind farms in summer*" (Article link)

- Experiences higher strain mainly due to extra degrees of freedom
- Load reduction → LCOE reduction → greater economical feasibility

The 6 additional degrees of freedom of a FOWT:

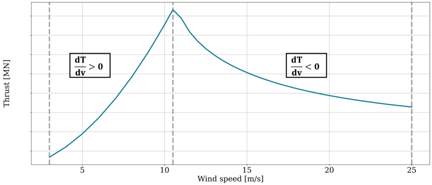


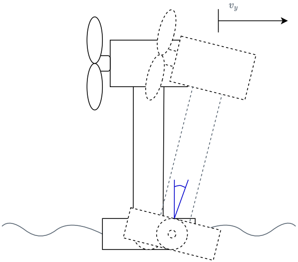
Introduction 4
Modelling
Controller Design
Test Results
Conclusion

Rotor thrust equation:

$$F_T(\theta, \Omega, v) = \frac{1}{2}\rho A_d v^2 C_T(\theta, \Omega, v) \quad (1)$$

Rotor thrust vs. wind speed with active controller:





$$v_{rot} = v_0 - v_y$$

Introduction 5
Modelling
Controller Design
Test Results
Conclusion

FLC and FATD have contradicting goals

In most FLC operating range: $\frac{\partial T_r}{\partial \theta} < 0$ but also $\frac{\partial F_T}{\partial \theta} < 0$

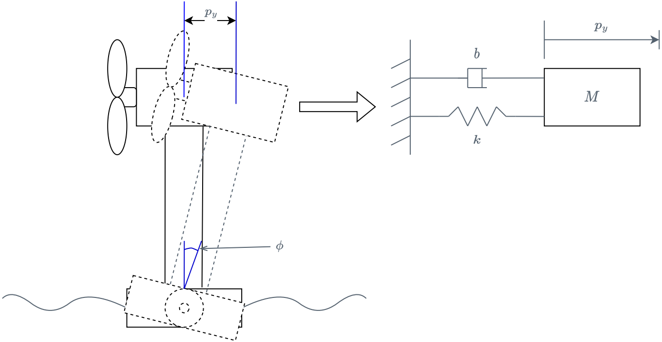
An example:

1. The turbine is moving forward: $v_y < 0$
2. Thus $\frac{\partial \Omega}{\partial v_{rot}} > 0$ and consequently $\Omega > \Omega_{ref}$
3. FLC: $\dot{\theta}_{ref} > 0 \rightarrow \dot{\Omega} < 0$ and FATD: $\dot{\theta}_{ref} < 0 \rightarrow \dot{F}_T > 0$

- Dynamics relevant to fore-aft motion included
- First principles modelling
- Component modelled individually
- Only fore-aft motion model included in presentation

$$\dot{v}_y = \frac{F_{rot} - bv_y - kp_y}{m} \qquad (2)$$
$$\dot{p}_y = v_y$$

$$k = (2\pi f_{eig})^2 m \quad , \quad b = 2\zeta\sqrt{km} \qquad (3)$$



Rotational Speed Control of Floating Wind Turbines

Martin H. Therkildsen

Introduction

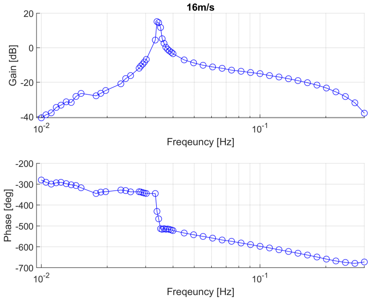
Modelling 8

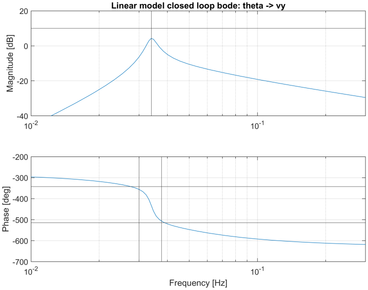
Controller Design

Test Results

Conclusion

Fore-aft motion model parameter fitting results:





VTS

OVERVEJ AT FINDE UD AF AT PLOTTE OVEN I HINANDEN

Linear model

Introduction

Modelling

Controller Design

Test Results

Conclusion

The resulting model:

- **States:** $\{p_y, v_y, \Omega, \Omega_{int}\}$
- **Input:** $\{\omega_{ref}\}$
- **Disturbance:** $\{v_{free}\}$
- **Outputs:** $\{p_y, v_y, \Omega\}$
- Stable
- Controllable and observable

Controller Design

Infinite-Horizon Linear-Quadratic Regulator with integral action

- LQR minimizes cost function to yield optimal controller gain
- Costs assigned to states and actuators
- Matlab: *lqr(A, B, Q, R, N)* <-VÆK
- Bryson's Rule used to find diagonal entries in Q and R

Integral action on rotor speed is necessary.

System is augmented with integral state $x_i = \int \Omega$:

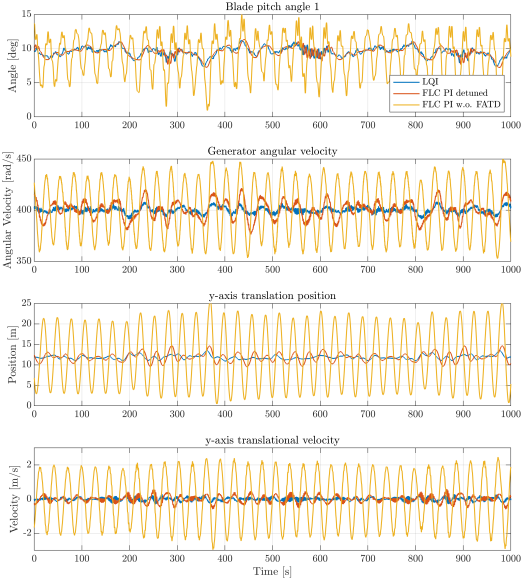
$$\dot{\bar{x}} = \begin{bmatrix} \dot{\hat{x}} \\ \dot{x}_i \end{bmatrix} = \begin{bmatrix} A & 0 \\ C_i & 0 \end{bmatrix} \bar{x} + \begin{bmatrix} B_u \\ 0 \end{bmatrix} \hat{u} \quad (4)$$

$$\bar{y} = \begin{bmatrix} C & 0 \end{bmatrix} \bar{x} \quad (5)$$

- Integral state is included in LQR algorithm
- Weight on integral state is awkward to place

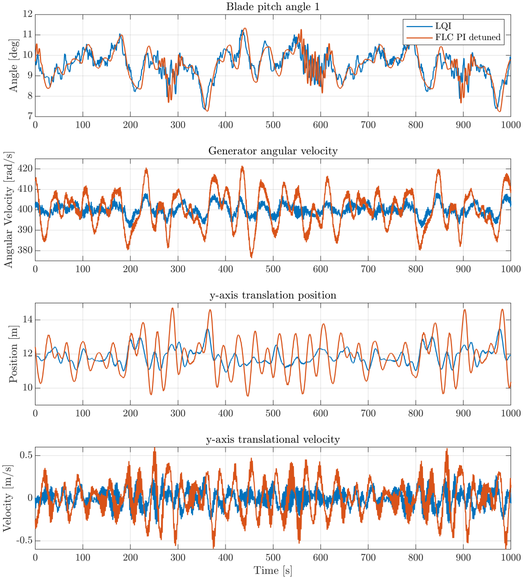
Test Results

VTS: 16 m/s - LQI vs. FLC vs. detuned FLC



Test Results

VTS: 16 m/s - LQI vs. detuned FLC



Introduction
Modelling
Controller Design
Test Results 13
Conclusion

Table: 1 Hz damage equivalent loads of LQI controllers

1 Hz damage equivalent loads		
LQI	FLC detuned	FLC
21760	25099	81343

Table: Blade pitch actuation sums

Blade pitch actuation sums			
	LQI	FLC detuned	FLC
Unfiltered	169.9	103.3	716.5
Filtered	67.6	63.7	557.7

Conclusion

- A simple linear model which implemented a mass-spring damper approximation of the fore-aft motion was proven to sufficiently capture the the fore-aft motion dynamics.
- Deviation observed between linear model and VTS behaviour with fixed-bottom FLC
- LQI controller successfully implemented in VTS and achieved satisfactory rotor speed tracking while greatly damping fore-aft motion
- LQI controller parameter recalculation for other OPs partly or fully improves performance - if higher frequency components are assumed to be filtered out.

Future work

- VTS implementation required inputting real states of fore-aft position and velocity to controller
- An estimator of tower top position is necessary
- Proper gain scheduling across full-load

Open for questions

AALBORG UNIVERSITY
DENMARK