# Using the Nested Control Co-design Strategy for Designing Floating Offshore Wind Turbines

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May 25, 2021; *Wind Energy Science Conference*

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# Introduction

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- The design of floating offshore wind turbines (FOWTs), and many other engineering systems, have often followed a sequential process[1]
- However, in FOWTs, there are **strong interactions between the structural dynamics and the controller**
- A sequential design process can produce unstable systems or overly conservative designs
- **Control co-design (CCD)** is a class of integrated design methods that **concurrently treats a dynamic system's physical and control aspects**, potentially overcoming some of the sequential limitations[2]
- Two common high-level organizational strategies for CCD are the simultaneous and nested approaches[3]
  - The **nested CCD formulation** is a two-level optimization problem where an **outer loop optimizes primarily the plant design with an inner loop that optimizes the control decisions for a given plant**
  - A common question is what strategy to use

[1] Jonkman et al. 2021
[2] Garcia-Sanz 2019; Allison, Guo, and Han 2014; Fathy et al. 2001
[3] Herber and Allison 2018; Sundarrajan and Herber 2021a

# → FOWT Design through LCOE

- Common top-level goals of any wind-based energy system design are to balance increasing the annual energy production using the incoming wind while minimizing the systems' building and operating costs
- These goals are captured by the **levelized cost of energy (LCOE)**[1] metric:

$$\text{LCOE} = \frac{\text{Total Lifetime Cost}}{\text{Total Lifetime Energy Output}} \tag{1}$$

- The lifetime costs (especially capital costs) are often directly linked to some of the plant design decisions
- The maintenance costs and the total lifetime energy output are more dependent on how the system is controlled

[1] Gros 2013

# → Nested CCD Problem

## Simultaneous CCD

$$\min_{\boldsymbol{\xi}, \boldsymbol{x}_c, \boldsymbol{x}_p} \quad o\left(\boldsymbol{\xi}, \boldsymbol{x}_c, \boldsymbol{x}_p\right)$$

$$\text{s.t.: } \dot{\boldsymbol{\xi}}(t) - \boldsymbol{f}(\cdot) = \boldsymbol{0}$$

$$\boldsymbol{h} = \begin{bmatrix} \boldsymbol{h}_o\left(\boldsymbol{x}_p\right) \\ \boldsymbol{h}_i\left(\cdot\right) \end{bmatrix} = \boldsymbol{0}$$

$$\boldsymbol{g} = \begin{bmatrix} \boldsymbol{g}_o\left(\boldsymbol{x}_p\right) \\ \boldsymbol{g}_i\left(\cdot\right) \end{bmatrix} \leq \boldsymbol{0}$$

## Nested CCD

Outer Loop

$$\min_{\boldsymbol{x}_p} \quad o\left(\mathcal{I}\left(\boldsymbol{x}_p\right), \boldsymbol{x}_p\right)$$

$$\text{s.t.: } \quad \boldsymbol{h}_o(\boldsymbol{x}_p) = \boldsymbol{0}, \; \boldsymbol{g}_o(\boldsymbol{x}_p) \leq \boldsymbol{0}$$

$\boldsymbol{\xi}^*, \boldsymbol{x}_c^* \uparrow \qquad \downarrow \boldsymbol{x}_p^\dagger$

Inner Loop

$$\min_{\boldsymbol{\xi}, \boldsymbol{x}_c} \quad o\left(\boldsymbol{\xi}, \boldsymbol{x}_c, \boldsymbol{x}_p^\dagger\right)$$

$$\text{s.t.: } \quad \dot{\boldsymbol{\xi}}(t) - \boldsymbol{f}\left(\cdot\right) = \boldsymbol{0}$$

$$\boldsymbol{h}_i\left(\cdot\right) = \boldsymbol{0}, \boldsymbol{g}_i\left(\cdot\right) \leq \boldsymbol{0}$$

- In the context of FOWT design, we can define an effective nested strategy problem partitioning as:
  - The outer loop deals with the minimizing LCOE with the plant-focused cost models and result from the inner-loop for energy production
  - The inner loop subproblem deals with maximizing the energy captured subject to the various constraints for a fixed-plant design (e.g., tower and platform geometry and materials)

# → Nested CCD in the Context of FOWT Design

- Some key advantages of the nested CCD strategy[1] are:
  - Each subproblem's structure is simplified and size reduced from the original simultaneous formulation (e.g., dynamics now considered with fixed $\boldsymbol{x}_p$)
  - Tailored optimization algorithms (and tolerances) can be used in the different subproblems that can leverage the simplified subproblem structure (e.g., QP or LQR or your current control design approach) or outer-loop global search
  - Parallelization of the control subproblems is possible
- In the context of FOWT design:
  - There is a natural division in the LCOE calculation between plant-focused cost models and control-dependent energy output and costs
  - Design load case subproblems in the inner-loop can be solved independently (i.e., more smaller problems rather than one large problem)
  - Linear dynamic models can be utilized to effectively capture key system dynamics which support tailored optimization algorithms (here quadratic programs)

[1] Sundarrajan and Herber 2021b

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# Linear Parameter-varying (LPV) Modeling and Validation

# → Modeling Considerations

- Often **linearized models** are used to study the system dynamics and design controllers:

$$\Sigma_o = \begin{cases} \dfrac{d\boldsymbol{\xi}_\Delta}{dt} = \boldsymbol{A}(w_o)\boldsymbol{\xi}_\Delta + \boldsymbol{B}(w_o)\boldsymbol{u}_\Delta \\ \boldsymbol{y} = \boldsymbol{g}(w_o) + \boldsymbol{C}(w_o)\boldsymbol{\xi}_\Delta + \boldsymbol{D}(w_o)\boldsymbol{u}_\Delta \end{cases} \quad (2)$$

  where $w_o$ characterizes the operating point for the linearized model
- One drawback with linearized model is their **accuracy diminishes as the system's behavior moves away from the initial operating point**
- Here, we will discuss the use of a particular **linear parameter-varying (LPV) model** to help overcome the drawbacks of single wind speed linearized models
- The use of various LPV models for wind energy application has been studied previously[1]

[1] Lescher, Zhao, and Martinez 2006; Bianchi, Mantz, and Christiansen 2005

# → LPV Model

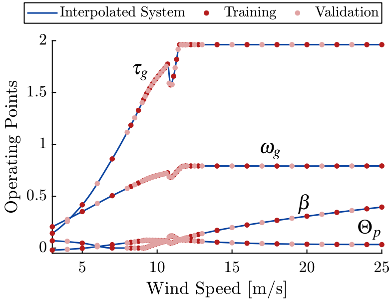
- Here, we will consider the single parameter case where the parameter $w(t)$ indicates the wind speed trajectory:

$$\Sigma_w = \begin{cases} \dfrac{d\boldsymbol{\xi}_\Delta}{dt} = \cancelto{0}{\boldsymbol{f}(w)} + \boldsymbol{A}(w)\boldsymbol{\xi}_\Delta + \boldsymbol{B}(w)\boldsymbol{u}_\Delta - \dfrac{\partial \boldsymbol{\xi}_o(w)}{\partial w}\dfrac{dw}{dt} \\ \boldsymbol{y} = \boldsymbol{g}(w) + \boldsymbol{C}(w)\boldsymbol{\xi}_\Delta + \boldsymbol{D}(w)\boldsymbol{u}_\Delta \end{cases} \tag{3}$$

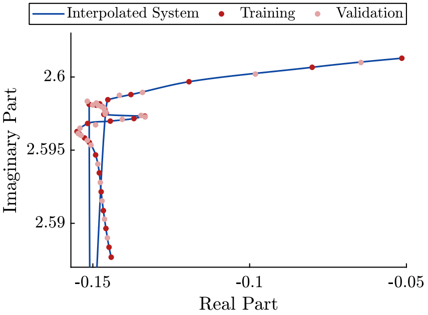
- To construct a continuous model with respect to the wind speed $w(t)$ from a finite set of linearized models, **element-wise matrix interpolation** is carried out for the given set of parameter values $\boldsymbol{W}$ (56 distinct wind speeds in this case)
- All the studies here are done using linearized models derived from the **IEA 15-MW reference turbine with OpenFAST**
- The turbine is supported by a **floating semisubmersible platform and a chain catenary mooring system**

# → Operating Point and Matrix Interpolation Verification Results

## Stationary Operating Points

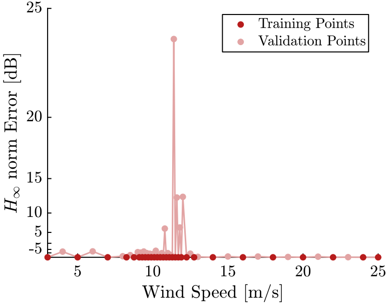



## One Eigenvalue of $A(w)$

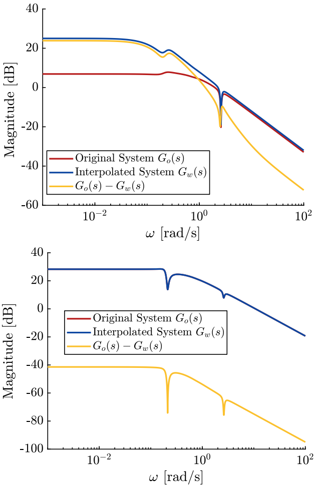


# → Frequency-Domain Verification Results

## $H_\infty$ Error using Validation Points



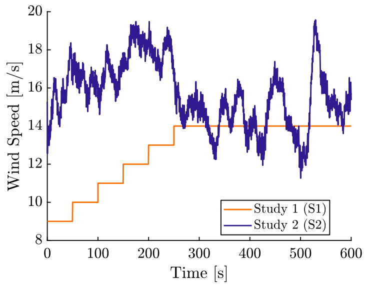

## Select Transfer Function Comparisons



# → Time-Domain Verification

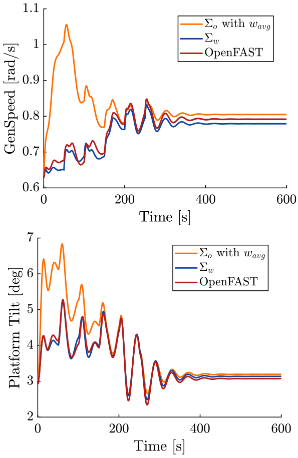
- This test allows us to check if the **interpolation-based model can capture the nonlinear dynamic response from OpenFAST** simulations
- For the same input trajectories, the resulting state trajectories are compared between the different models
- Two different inputs were simulated (shown in the figure on the right)

## Wind Inputs for the Test Scenarios

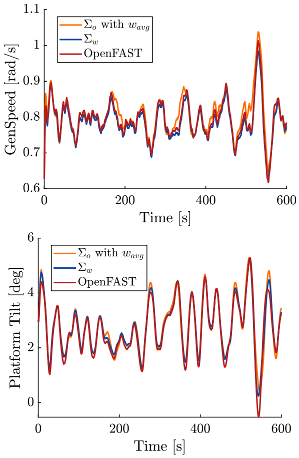


# Time-Domain Verification Results

## Results for Stepped Wind Test Scenario




## Results for Turbulent Wind Test Scenario



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# Control Co-design (CCD) Problem Formulation

# → Control Co-Design Problem Formulation

- The overall objective of the CCD problem is to minimize the LCOE
- The complete optimization problem is:

$$\min_{\boldsymbol{x}_p} \quad \mathrm{LCOE}(\boldsymbol{x}_p) = \frac{C_n(\boldsymbol{x}_p)}{E_n(\boldsymbol{x}_p)} \tag{4a}$$

$$\text{subject to:} \quad \boldsymbol{L}_p \leq \boldsymbol{x}_p \leq \boldsymbol{U}_p \tag{4b}$$

- $E_n(\boldsymbol{x}_p)$ is determined using a **year-long energy production calculation weighting the results of the inner-loop control optimization problems for various design load cases**
- The cost of the individual subsystems is obtained from a cost and scaling model developed in Ref.[1]
- In this study, the **platform's mass is the single plant design variable**
  - A sensitivity study is carried out to see the impact of this variable
  - Capital cost of the system is directly proportional to the platform mass

[1] Fingersh, Hand, and Laxson 2006

# Control Subproblem for a Specific Design Load Case

- The control subproblem's goal is to understand the **impact of the control decisions on stability, power production, and ultimately the LCOE design objective**
- An **open-loop optimal control** problem is constructed to **maximize the power** produced for a given design load case (DLC):

$$\int_0^{t_f} P(t)\mathrm{d}t = \int_0^{t_f} \eta_g \tau_g(t)\omega_g(t)\mathrm{d}t \tag{5}$$

- The LPV models are used as dynamic constraints for this optimal control problem
- A linearized power constraint is included to ensure the **power generated by the turbine does not exceed the rated power**

$$\tau_g\omega_{g,\max} + \tau_{g,\max}\omega_g \leq P_{\max} + \tau_{g,\max}\omega_{g,\max} \tag{6}$$

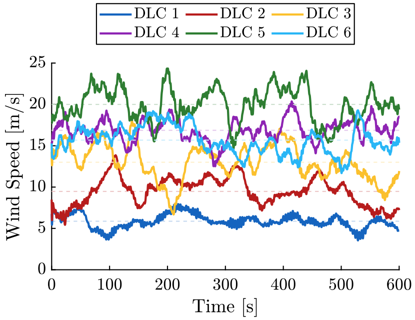
- Additional simple bound constraints are included to limit the blade pitch, generator torque, generator speed, and platform pitch:

$$0 \leq \tau_g(t) \leq \tau_{g,\max},\ 0 \leq \beta(t) \leq \beta_{\max},\ \omega_g(t) \leq \omega_{g,\max},\ \Theta_p(t) \leq \Theta_{p,\max} \tag{7}$$

# → Design Load Cases and Sensitivity Study

- Six different DLCs are considered
- **Platform pitch tilt $\Theta_p$ is constrained to four different values**, $(3°, 4°, 5°, 6°)$
- LPV models are constructed for eleven different values of the platform mass
- Similar to the previous element-wise matrix interpolation based on $w(t)$, intermediate mass can be obtained

**Six Considered DLCs**



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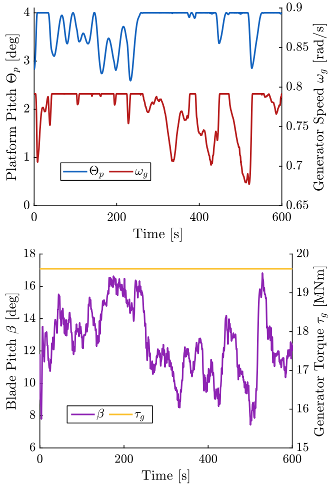
# Results and Discussion

# Results for a Single Control Subproblem

- The optimal control results for case with $m_r = 0.7$, DLC 6, and $\Theta_p \leq 4°$ are presented in detail here
- DLC 6 is in the rated-power region, so we might expect pitch control to be active and the generator torque and generator speed to be held roughly constant
- We see that the **path constraints are active**
- However, to satisfy the platform pitch constraints, we see that the **generator speed is compromised relative to the desired value**

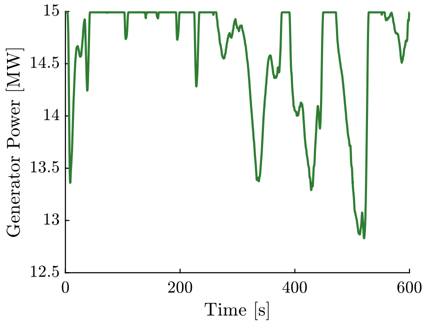
## States and Controls



# → Power Production Results for a Single DLC

- Power is calculated as $P = \tau_g \omega_g$
- Since the generator speed is compromised in favor of satisfying pitch constraints, we see that the **power generated is affected too**
- To understand how the pitch constraints affect the power production for all the masses, we look at the results of the sensitivity study

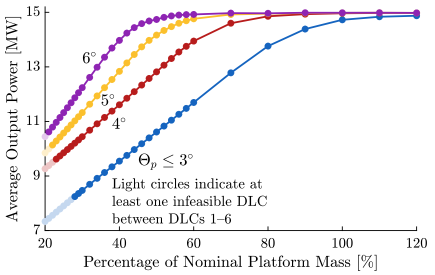
**Power**



# → Average Output Power vs. Platform Mass

- **Average power for DLC 6 vs platform mass** is shown for the four different values of $\Theta_{p,\max}$
- To satisfy smaller values of $\Theta_{p,\max}$, the **blade pitch is active** and the power is sacrificed
- We see that **heavier platforms** satisfy the stability constraints with **little to no compromise on power** generation
- In comparison, **lighter platforms have to sacrifice power generation**
- But this result is for a single DLC, next we see the complete study that shows the variation of LCOE combining all DLCs

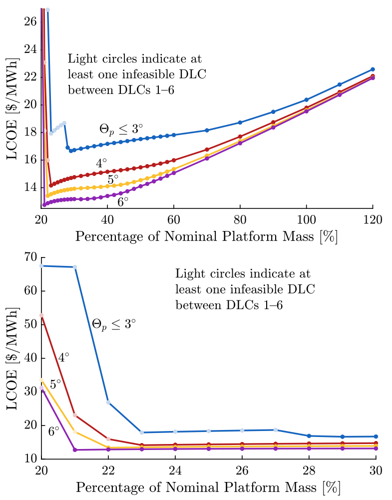
**Power vs. Mass**



# → LCOE vs. Platform Mass

- Combining the DLCs, we can determine the total energy output
- Some values of the constraints are **infeasible**, and they are included with **zero generated energy**
- As the platform mass increases the power produced on average increases
  - Consequently, the capital cost increases and so does the LCOE
  - This implies the presence of an optima without the additional constraints
- While keeping the other plant parameters constant, we see that the lowest LCOE for $\Theta_p \leq 6^\circ$, is achieved using $30 - 60\%$ of the nominal platform mass

## LCOE vs. Mass



# → Conclusion

- This study demonstrates how **LPV models can be used to derive meaningful CCD results for complex problems like FOWT design**
- These results are subject to modeling assumptions, optimal control operation, and lack of safety factors, but represent progress in understanding the key design trade-offs
- Additionally, the hydrodynamic and hydrostatic stability of the different platforms have not been evaluated in this study; these considerations will also limit the bounds on the platform mass and impact the final design
- It remains **future work to incorporate more detailed outer-loop plant design optimization**, including the impact of other plant decisions like tower hub height and blade length
- Additionally, the optimal control results here can serve as a basis for more robust, implementable control architectures

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# Questions?

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# → Plant and Control Considerations of a FOWT

- The plant design of a FOWT involves design decisions for several individual subsystems and considerations of stability, cost, and energy production[1]
    - The primary elements of a FOWT are the rotor, drivetrain, nacelle, tower, and support structure
- The **primary mode of control of a wind turbine will depend on the wind speed**, so specific operating regions are often defined based on the wind speed[2]
- The two primary control inputs for wind turbines are the pitch angle of the turbine blades (commonly called blade pitch) and the torque produced by the generator
    - In **below-rated wind speeds, varying the generator torque** is the primary mode of control of the turbine
    - At **rated wind speeds**, the generator torque is held constant, and the **blade pitch is varied** in a process called maximum power point tracking

[1] Johannessen 2018 [2] Pao and Johnson 2009; Moriarty and Butterfield 2009