Design of Floating Offshore Wind Turbines Using OpenMDAO and Dymos

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Two months with THE UNIVERSITY OF MEMPHIS *affiliation*

Work based on collaborations with

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VL Offshore Engineering Solutions

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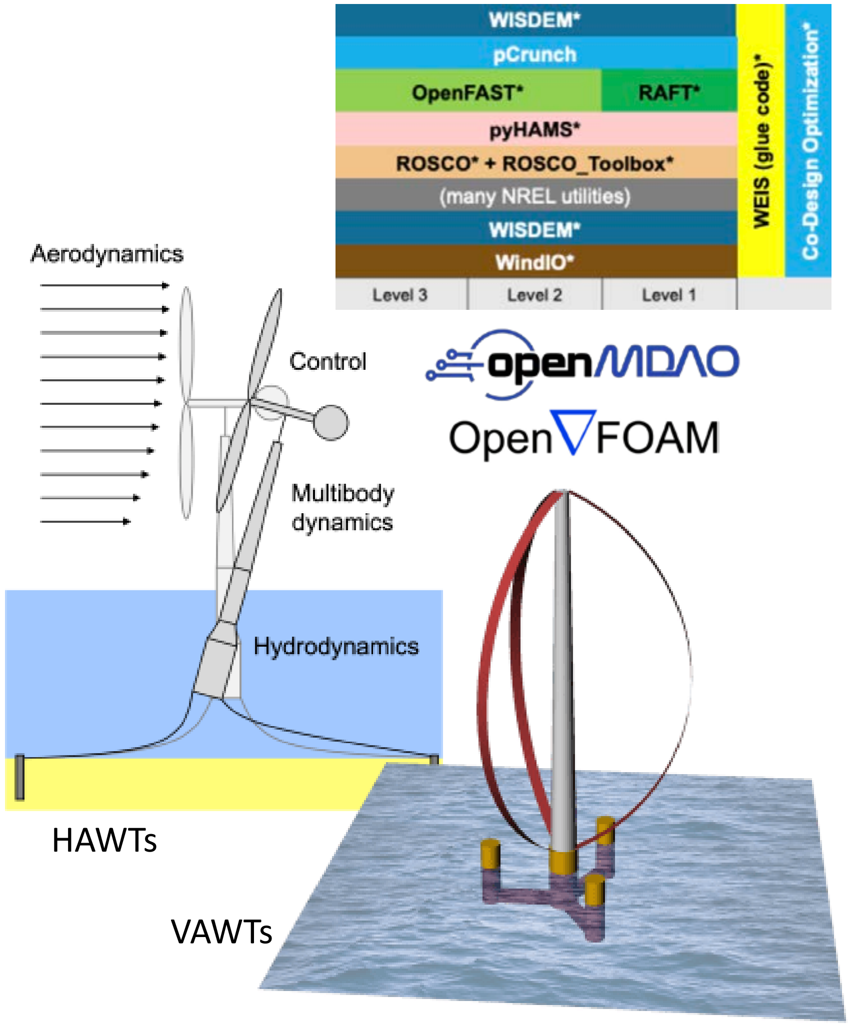
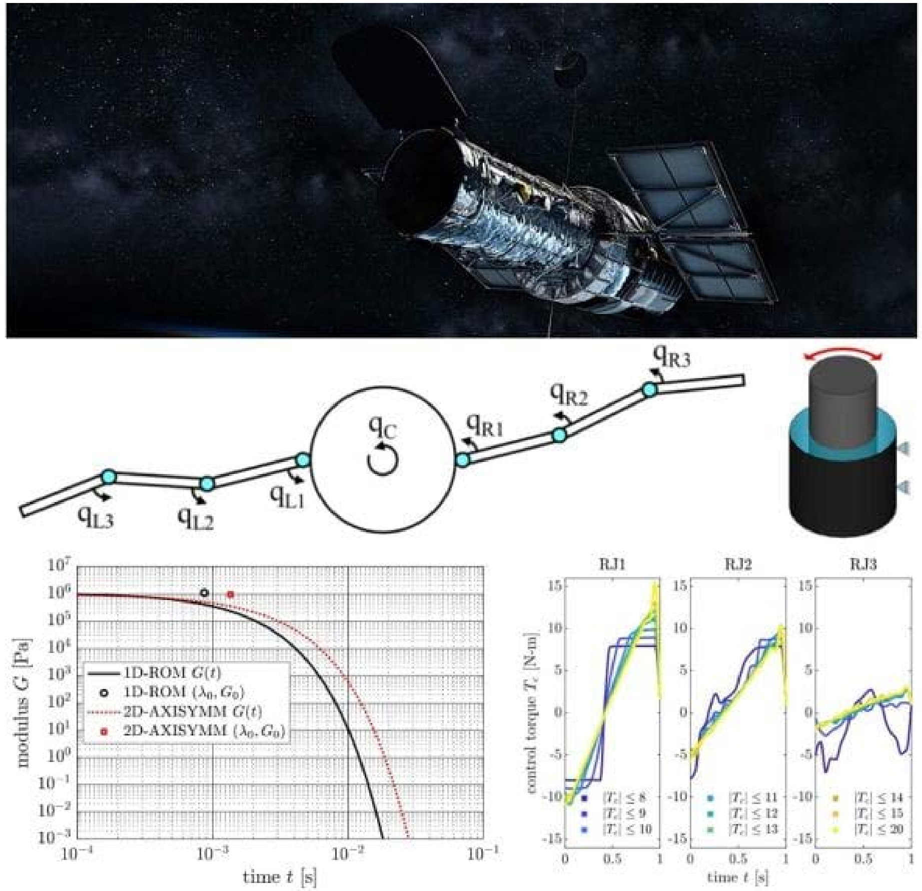
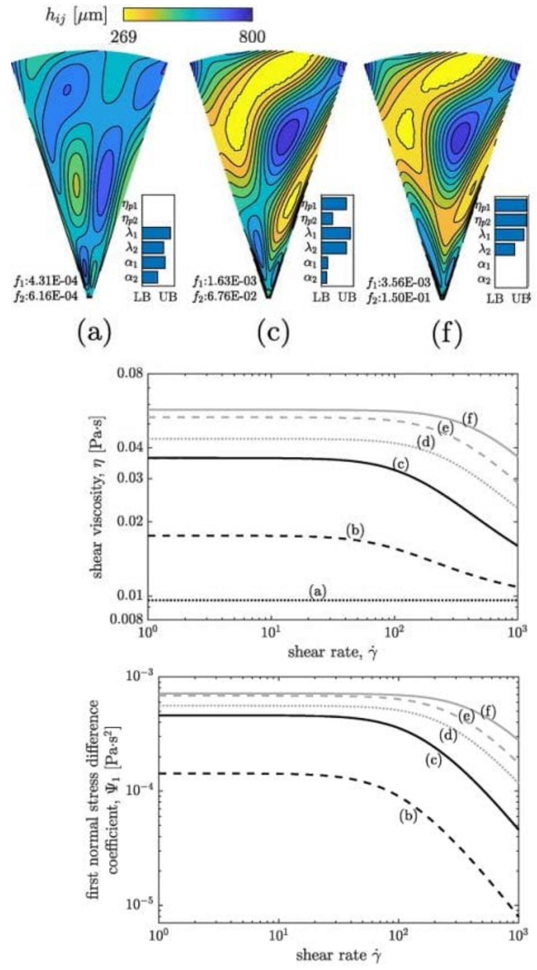
Lee Research Group @ UofM - research topics and capabilities



System modeling and design, MDAO studies



Dynamic system control co-design (CCD)



Complex fluids + geometry design

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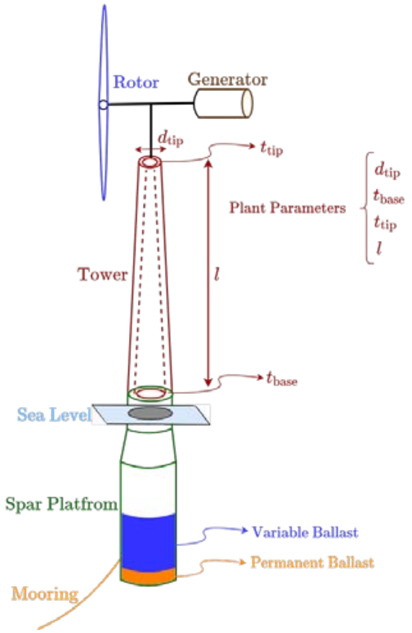
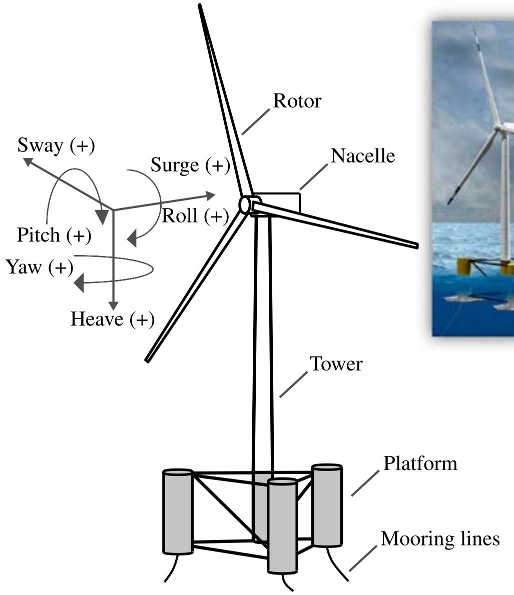


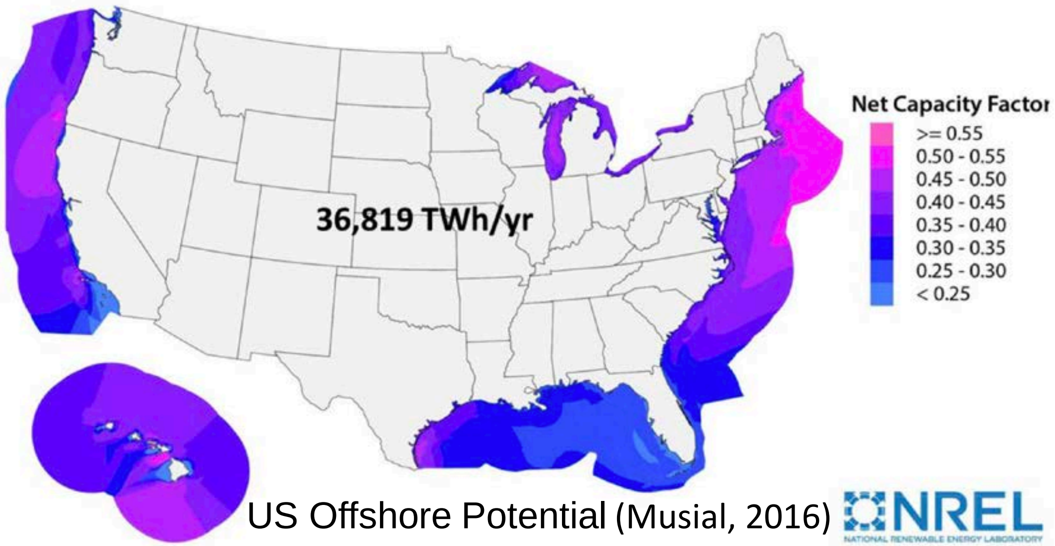


Floating Offshore Wind Turbine (FOWT) system overview

- Offshore wind energy can go larger, which also means higher efficiency.
  - Shipyard-built system – No transportation constraints
  - Current development projects are mostly 5-18MW scales
  - The largest land-based turbines are mostly in 1-2.5MW scales (utility-scale wind turbines)

- FOWTs enable the installation of wind farms in deep-water regions.
  - 60% of offshore wind energy resides in deep-water regions
  - Strong and steadier wind resources
    : The Gulf of Mexico, the Gulf of Maine, etc.

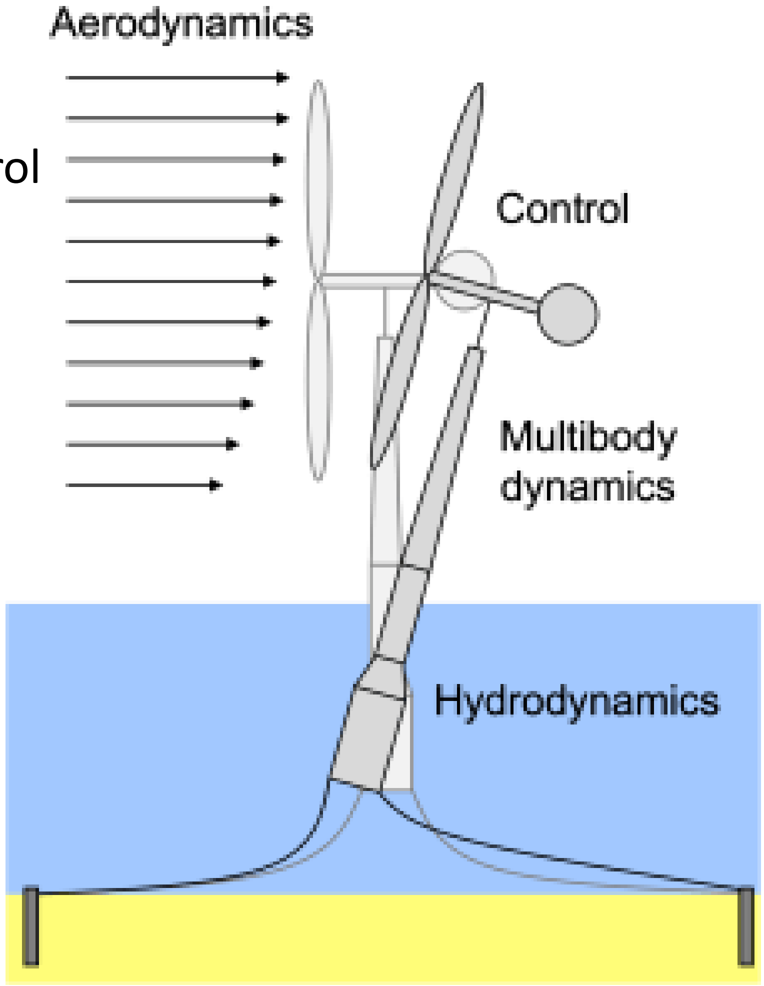
- Disadvantages
  - High capital and operating/maintenance costs
  - Less-explored technologies



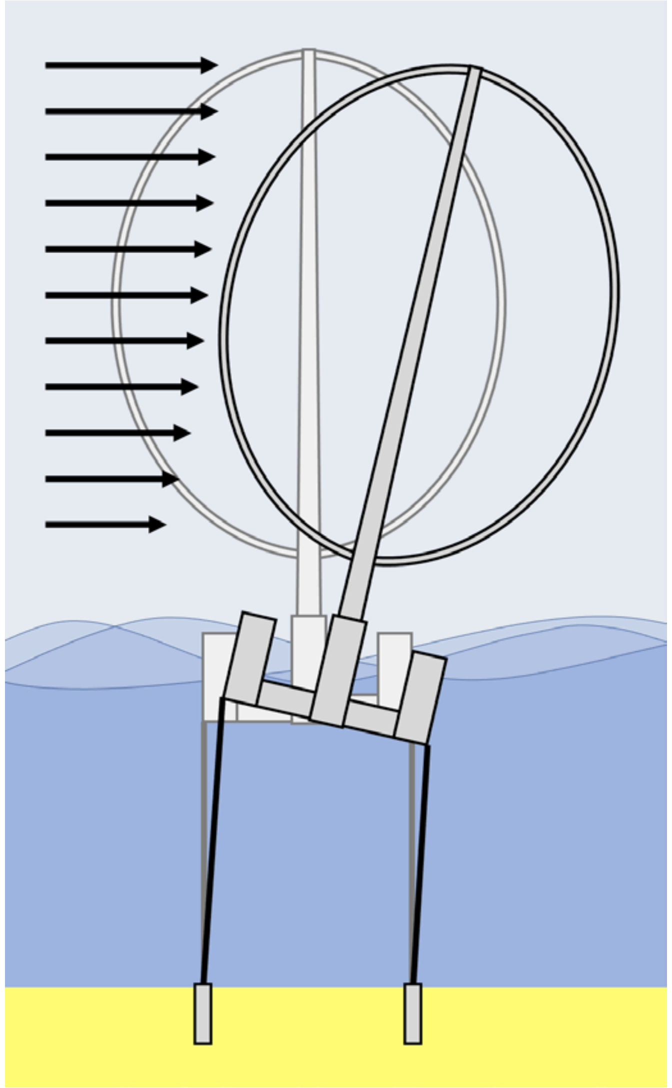
US Offshore Potential (Musial, 2016)

Floating Offshore Wind Turbine (FOWT) system overview

- Multidisciplinary nature of the FOWT system
  - System components
    - **Rotor** - blades, hub, pitch mechanism
    - **Drivetrain** and **generator**, Vertical-axis wind turbine intra-cycle control
    - **Controller** (PID, NMPC, OLOC), various sensors, LIDAR (Scholbrock, 2016)
    - **Tower** and **yaw device** (important for farm-level optimization)
    - **Floating platform** and **ballast** system
    - **Mooring lines** and fairleads, Tension active control (Li & Wu, 2016)
    - **Anchoring system**
  - Environmental interactions
    - **Wind** aerodynamic loads, aerodynamic wakes, turbulence
    - Platform **hydrostatics** and **hydrodynamic** forcings
    - Ocean **current** and **waves**
  - Costs, performances, constraints, and other factors
    - **Design Load Cases** and **failure modes** (motion, stress, fatigue, etc.)
    - **Annual Energy Production**
    - **Capital expenses**, **operating expenses**
    - Manufacturability **constraints**



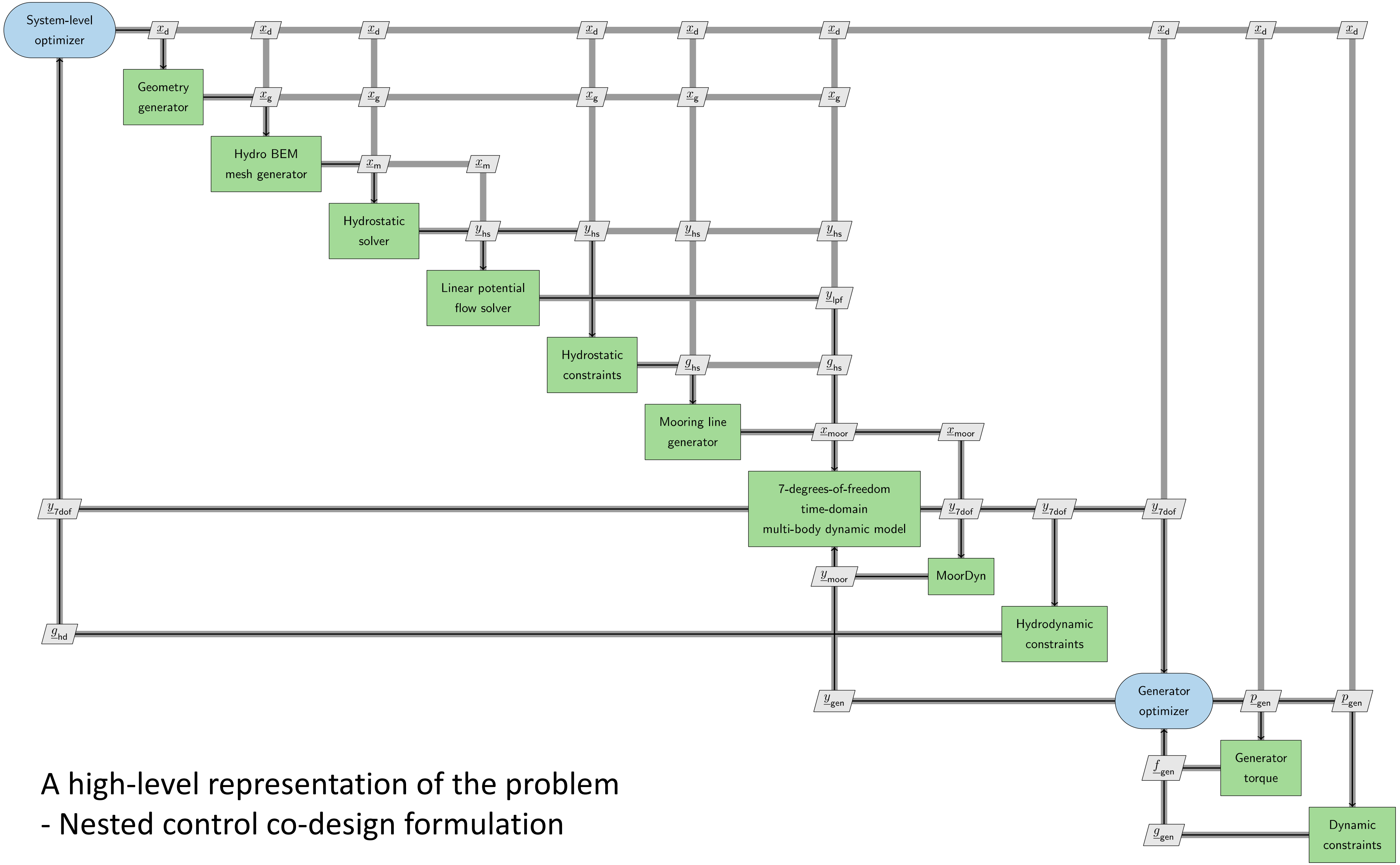
MDO implementations for numerical models and design elements



- MDO motivation
  - A hierarchical system-level + subsystem-level design problems of the vertical-axis wind turbines.
  - The system model became too complicated.
  - With many disciplinary domain models, a sequential analysis strategy was not always efficient.
  - The hierarchical system-level + subsystem-level design approach required a derivative of multi-level formulation, such as the ATC.

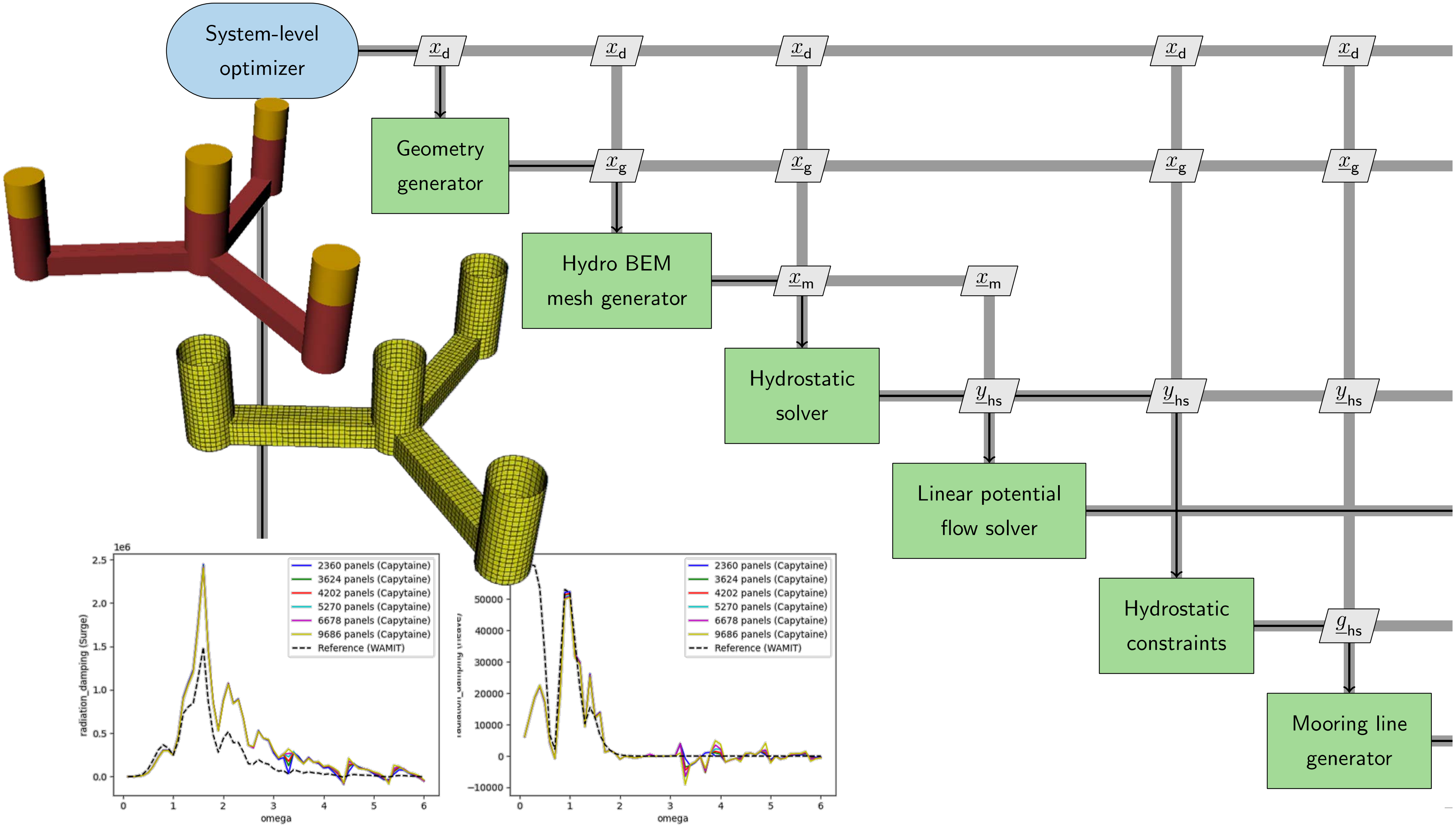
- Started looking into using OpenMDAO as an optimization driver
  - Many physics domains – created interfaces to OpenMDAO.
  - Reformulated problem structures.
  - Multi-level formulation is still ongoing task.

MDO implementations of numerical models and design elements

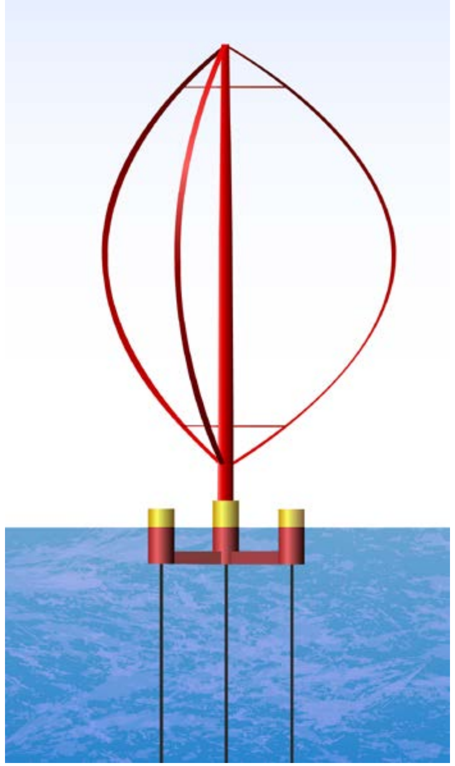


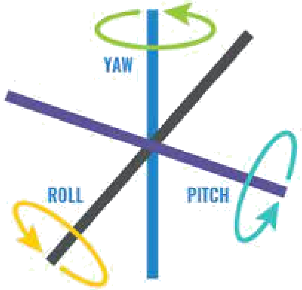
A high-level representation of the problem
- Nested control co-design formulation

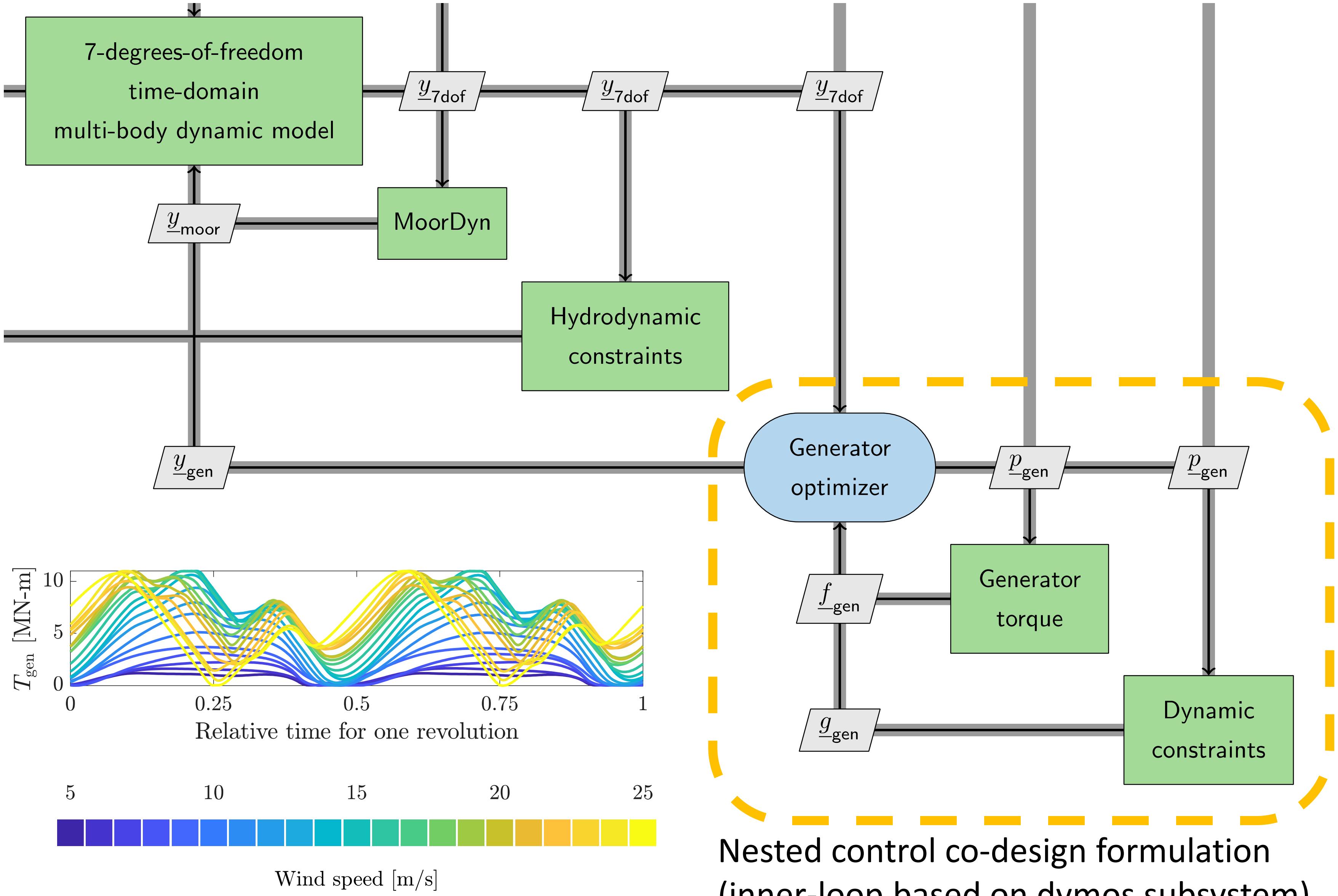
MDO implementations of numerical models and design elements



MDO implementations of numerical models and design elements

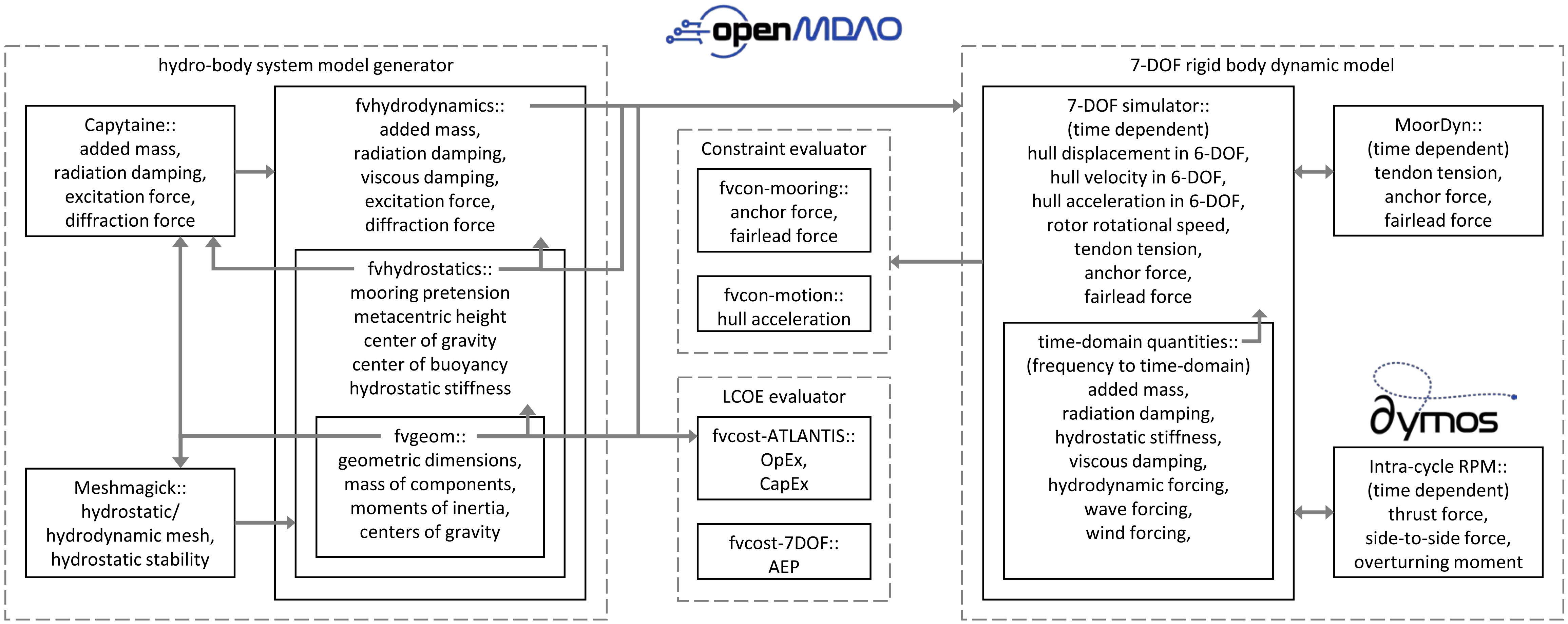






Nested control co-design formulation (inner-loop based on dymos subsystem)

The use of openMDAO and dymos in the FOWT design



Needs for next generation MDO approaches that can further enhance design processes

- Design practices in multi-institutional collaborations cannot be easily integrated.

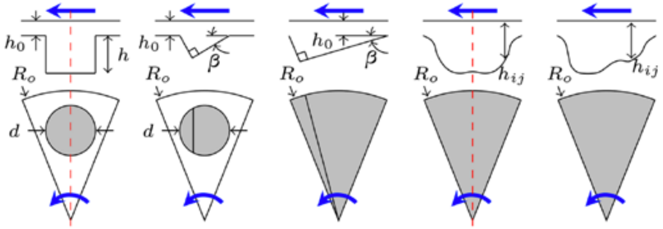
  Example: the FOWT design process:

  - Floating platform experts – floater design
  - Wind turbine aerodynamics experts – tower and blade design
  - Experimental fluids experts – wind tunnel experiments
  - System design experts – communicate with all other groups and create corresponding lower-fidelity models
- Modern engineering systems are too complicated, so that system engineers may not be able to understand all aspects of the system.
- Integrated system analysis and design tools are not readily available in many domains.
- Human expert's heuristic decisions are sometimes valuable. Mathematical expressions do not always reflect the exact reality.

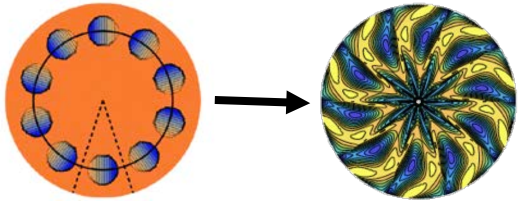
Ongoing work and future plans

- Reassess necessities of conventional design limits and constraints.
  - Remove predefined shape or design parameterization
  - Allow full freedom in design

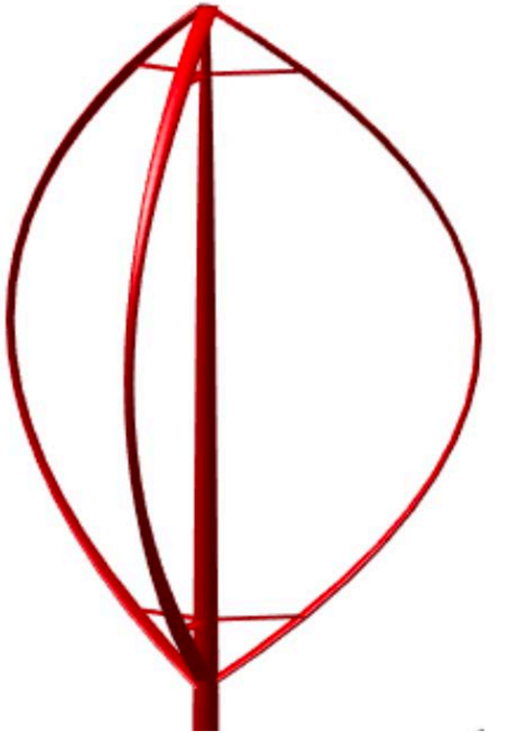
Designing with viscoelastic material functions
to achieve system-optimal solution (Lee 2019)

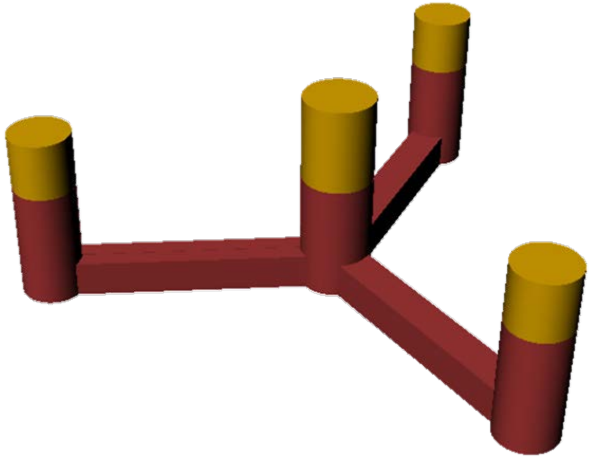


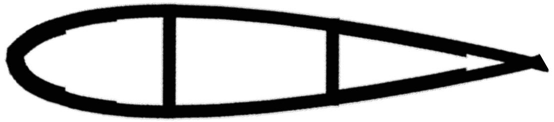
Allowing design freedom via
geometric parameterizations (Lee 2017)



(Schuh 2017, Lee 2017)







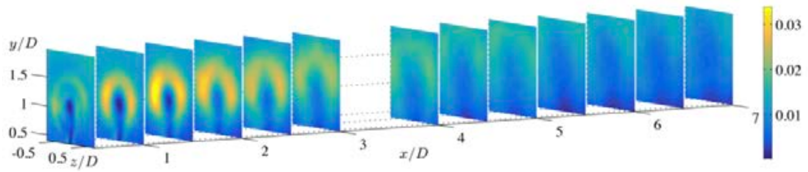
Ongoing work and future plans

- Number of scalars in the hydrodynamic coefficients in varied frequency range are large
  - Connecting variables between disciplinary models need to be reduced.
  - Proper orthogonal decomposition (POD) based dimension reduction is being explored.

<u>General IDF formulation</u>

$$
\begin{aligned}
\underset{\mathbf{x},\hat{\mathbf{y}}_i}{\text{minimize}} \quad & f\left(\mathbf{x}, \mathbf{y}\left(\mathbf{x}, \hat{\mathbf{y}}\right)\right) \\
\text{subject to} \quad & \mathbf{g}\left(\mathbf{x}, \mathbf{y}\left(\mathbf{x}, \hat{\mathbf{y}}\right)\right) \leq \mathbf{0} \\
& \mathbf{h}\left(\mathbf{x}, \mathbf{y}\left(\mathbf{x}, \hat{\mathbf{y}}\right)\right) = \mathbf{0} \\
& \mathbf{h}_c = \hat{\mathbf{y}} - \mathbf{y} = \mathbf{0} \qquad \# \text{ coupling constraints} \\
\text{where} \quad & \mathbf{y} = \{y_i : \forall i = 1, \cdots, N\} \\
& \hat{\mathbf{y}} = \{\hat{y}_i : \forall i = 1, \cdots, N\} \qquad \# \text{ coupling variables}
\end{aligned}
$$

<u>Turbulent stress ($\overline{uu}/U$) reconstructed using the POD</u>



Hamilton (2016) Phys. Fluids

Number of required coupling variables/constraints for hydrodynamics with 60 periods = 4095

Added mass term: 1320 variables

$A_{ij}(\omega)$ =

A11	0	0	0	A15	A16
0	A22	0	A24	0	A26
0	0	A33	A34	A35	0
0	A42	A43	A44	0	A46
A51	0	A53	0	A55	A56
A61	A62	0	A64	A65	A66

Viscous damping stiffness term: 6 variables

V_{ij} =

V11	0	0	0	0	0
0	V22	0	0	0	0
0	0	V33	0	0	0
0	0	0	V44	0	0
0	0	0	0	V55	0
0	0	0	0	0	V66

Radiation damping term: 1320 variables

$B_{ij}(\omega)$ =

B11	0	0	0	B15	B16
0	B22	0	B24	0	B26
0	0	B33	B34	B35	0
0	B42	B43	B44	0	B46
B51	0	B53	0	B55	B56
b61	B62	0	B64	B65	B66

Froude-Krylov force: 720 variables

$F_{FK}(\omega)$ =

$F_{FK}1$	$\phi_{FK}1$
$F_{FK}2$	$\phi_{FK}2$
$F_{FK}3$	$\phi_{FK}3$
$F_{FK}4$	$\phi_{FK}4$
$F_{FK}5$	$\phi_{FK}5$
$F_{FK}6$	$\phi_{FK}6$

Hydrostatic stiffness term: 9 variables

C_{ij} =

0	0	0	0	0	0
0	0	0	0	0	0
0	0	C33	C34	C35	0
0	0	C43	C44	C45	0
0	0	C53	C54	C55	0
0	0	0	0	0	0

Diffraction force: 720 variables

$F_D(\omega)$ =

F_D1	ϕ_D1
F_D2	ϕ_D2
F_D3	ϕ_D3
F_D4	ϕ_D4
F_D5	ϕ_D5
F_D6	ϕ_D6

Ongoing work and future plans

- Distributed MDAO that involves heterogeneous decision-making processes
  - Aim: Enabling effective collaborative design processes in large groups of experts through the effective exchange of design decisions and knowledge.
  - Use of the MDAO framework in heterogeneous decision-making processes beyond computational models.
    - Subsystem-level high fidelity computational models
    - System-level low fidelity computational model
    - Quantitative and qualitative human expert inputs, hardware-in-the-loop optimization, etc.
  - System-level lower-fidelity models and corresponding high-fidelity subsystem models need to be concurrently optimized.

Thank you.

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