# OpenTurbineCoDe (OTCD): An Open-Source Floating Offshore Wind Turbine Multidisciplinary Control Co-Design Optimization Framework

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**Track 3: Offshore Wind**

## Introductory Summary

This presentation will introduce a mixed-fidelity multidisciplinary control co-design optimization (MCCDO) framework for floating offshore wind turbines. We will describe a modular computational framework for the modeling, optimization, and control of primary structures coupled to the surrounding air, water, and actuator dynamics.

**Keywords:** *Control Co-Design, Floating Offshore Wind Turbine, Multidisciplinary Design Optimization*

## Introduction

The goal of the Department of Energy (DOE) Advanced Research Projects Agency-Energy (ARPA-E) Aerodynamic Turbines Lighter and Afloat with Nautical Technologies and Integrated Servo-control (ATLANTIS) Program [1] is to develop new technologies for floating offshore wind turbines, or wind farms, using the discipline of control co-design (CCD.) In this context, we aim to develop a computationally efficient optimization framework for design of floating offshore wind turbines [2]. Our specific aim is to utilize high-fidelity structural, aerodynamic, aero-structural tools, and to derive control-oriented reduced- or low-order models directly from the high-fidelity tools. We are proposing a mixed-fidelity modeling approach which means that we are also using low- and mid-fidelity tools when necessary. This research is conducted by a multidisciplinary team consisting of Rutgers University, University of Michigan, Brigham Young University, and the National Renewable Energy Laboratory (NREL).

## Methods

The computational framework, called *OpenTurbineCoDe* [3], is designed to integrate, where possible, traditional structural, aerodynamic, aeroelastic models (e.g., *OpenFAST* [4]) and advanced control algorithms with higher fidelity simulation tools including Reynolds-averaged Navier–Stokes (RANS) solvers, and three-dimensional structural finite element solvers. All the high-fidelity tools used in this research provide numerically exact gradients to facilitate both efficient optimization and local linearization for control implementation.

**Main framework and the Graphical Use Interface (GUI):** The so-called master framework employs a "parent-child" organization, and is the overarching code that controls the entire workflow. This code and the GUI interprets external and user commands and data, and calls the relevant submodules. Although the framework is designed to run automatically in a parallel processing environment, a GUI is provided to make the program accessible, set up cases, and to run low-fidelity simulations. The *pyQT5*-based GUI is composed of six tabs, including main options, geometry, aerodynamics, structures, aero-structural, control co-design tabs. These submodules are “modular” and can be called as standalone GUIs.

**Geometry generation:** The geometry module allows the user to design the turbine blade "wetted" geometry, and to export into different formats. The module first loads the blade geometry file in AeroDyn format, a module in *OpenFAST*. The user is allowed to edit the tabulated geometry information to modify the blade shape, including airfoil type, blade twist, and chord distributions. The geometry information is used for generating the turbine blade for different solvers. For low- and mid-fidelity models, text-based output files are generated. For RANS simulations, a CAD-based model, and the surface mesh can be generated using several tools including *BB3D* [5], *Salome* [6], and *PGL* [7] codes.

**Structural modelling:** The structural module provides multi-fidelity static and dynamic structural simulations. The *TACS* [8] code is implemented as the high-fidelity structural solver for analyzing wind turbine blades [9]. Effective parameters are extracted from the high-fidelity model for use in the reduced-order model. The low-fidelity structural module implements the geometrically exact beam theory with the use of BeamDyn, a module in *OpenFAST*. This tool captures nonlinear behavior of large wind turbine blades, is used in *OpenFAST*-based control implementation and control co-design.

**Aerodynamic modelling:** Regarding aerodynamics, three numerical tools are available in the framework. Low-fidelity modeling is based on the blade element momentum (BEM) theory [10]. The mid-fidelity model [11] uses the *OpenFOAM*-based *turbinesFoam* code [12], which employs the actuator line model (ALM). Finally, the RANS solver *ADflow* [13,14] provides three-dimensional steady-state, fully turbulent solutions of the flow field past the rotor blades, and its sensitivities via the adjoint method [15]. Both modeling and simulation tools inform the design process as discussed below.

**Aeroelastic modelling:** Two aero-structural analysis tools are available to the user. *OpenFAST* enables low-cost steady and unsteady simulations, while high-fidelity steady-state analysis and optimization capabilities are available via the *MACH* framework [16], which combines *ADflow* and *TACS* solvers. The coupled adjoint approach implemented in *MACH* [17] enables gradient-based optimization of the turbine rotor using the tightly coupled aerostructural model, as presented in [18].

**Reduced order modelling:** A control-oriented reduced-order model (ROM) that captures the behavior of the main components of a FOWT is derived. The equations of motion are written employing Euler-Lagrange mechanics, and assuming interconnected lumped elements [19]. The model consists of multiple degrees of freedom that can be enabled or disabled. Actuator dynamics and non-linearities are also considered in the model. Although the ROM is intrinsically non-linear, it is linearized about an operating point, and used for controller synthesis.

**Advanced controller:** Several controllers are derived to maximize the power coefficient while mitigating the loads on the structure. A mixed control architecture of $H\infty$ controllers [20] and reference governors (RG) is proposed [21]. Appropriate $H\infty$ controllers reject external perturbations, while RG deals with constraints on the system [22, 23]. Such arrangement [24,21] is unique, and allows the system to satisfy command tracking despite disturbances and fulfill constraint requirements.

**Optimization and control co-design:** Traditional optimization [25], and control co-design optimization [21, 26] of the wind turbine are handled using multiple mixed-fidelity approaches. For traditional design optimization, the high-fidelity model is used to capture the aeroelastic blade response to any change in the structural and geometrical design variables. The average power production and mass of the rotor are obtained via *MACH*, and are linearly combined in the optimization objective. Non-linear constraints on thrust, stress, and tip displacement are integrated with *OpenFAST*-based constraints on fatigue and extreme (unsteady) loads. Control co-design optimization is implemented in two ways. In the first (baseline) method, a framework is developed using an aero-hydro-servo-structure coupled model in *OpenFAST*. The aerodynamic and structural parameters are updated automatically [26]. The Reference Open-Source Controller (ROSCO) is tuned automatically [27]. In the second method, the ROM parameters are automatically deduced from *TACS* and *OpenFAST*, and the advanced controller is tuned.

## Acknowledgments

This research is supported by the ARPA-E ATLANTIS award DE-AR0001186 entitled “Computationally Efficient Control Co-Design Optimization Framework with Mixed-Fidelity Fluid and Structure Analysis.”

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