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DEVELOPMENT OF A CONTROL CO-DESIGN MODELING TOOL FOR MARINE HYDROKINETIC TURBINES

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ABSTRACT

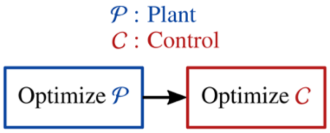
This report describes the ongoing and planned development of the software package CT-Opt (Current/Tidal Optimization), a control co-design modeling tool for marine hydrokinetic turbines. The commercialization of these turbines has faced significant challenges due to the complex, multidisciplinary nature of their design and the extreme environmental conditions of their operation. This project aims to create a modeling tool that will enable the efficient design of robust, cost-competitive hydrokinetic turbine systems. Rather than using traditional optimization methods, CT-Opt combines multiple models across a range of fidelities to enable coupled optimization of the system design and system controller via a control co-design approach. With this method, the parameters that affect system performance are considered more comprehensively at every stage of the design process. The lowest-fidelity, frequency-domain model called by CT-Opt is RAFT (Response Amplitudes of Floating Turbines), which was originally developed by the National Renewable Energy Laboratory (NREL) to model response amplitudes of floating offshore wind turbines. The highest-fidelity, time-domain model is OpenFAST, which was developed by NREL for land-based and offshore wind turbines. As part of the CT-Opt project, new functionalities will be added to RAFT and OpenFAST to enable the accurate simulation of fixed and floating marine hydrokinetic turbines. In addition to expanding the capabilities of RAFT and OpenFAST, new mid-fidelity models will be developed. These models will be based on RAFT and OpenFAST and will consist of linearized, state-space models derived from the fully coupled, nonlinear OpenFAST equations and derivative function surrogate models that approximate the nonlinear system behavior. Each model will be coupled with controllers to allow control co-design methods to be applied both within models and across fidelity levels, enabling efficient system optimization.

Keywords: design optimization, modelling/simulation, renewable energy

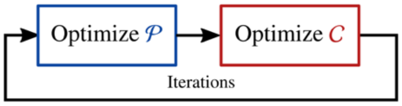
1. INTRODUCTION

The marine energy industry has experienced significant growth in the past decade, with the U.S. National Hydropower Association targeting marine energy deployments of at least 50 MW by 2025, 500 MW by 2030, and 1 GW by 2035 [1]. Energy generation from tides, ocean currents, and rivers has the potential to comprise a significant portion of deployments, as the technical resource from these sources made up 9% of the total U.S. electricity generation in 2019 [2]. Increasing the availability of validated, open-source tools for hydrokinetic turbine (HKT) design and optimization will allow the marine energy industry to more rapidly converge on robust, cost-effective designs that can be deployed across a range of scales to meet the diverse needs of the marine and electricity sectors.

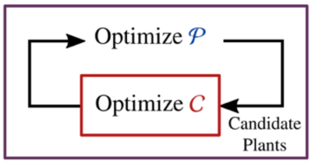
The design of HKT systems is multidisciplinary, and system-level modeling tools must incorporate aspects of hydrodynamics, structural dynamics, power electronics, controls, and more to accurately predict and optimize turbine performance. The complex nature of the design space coupled with extreme operating environments presents significant challenges to the development of reliable, cost-competitive turbines. The Submarine Hydrokinetic And Riverine Kilo-megawatt Systems project administered by the U.S. Department of Energy Advanced Research Projects Agency-Energy aims to address these challenges by funding novel HKT systems that utilize advanced design methodologies such as control co-design (CCD) [3]. As a project participant, the National Renewable Energy Laboratory (NREL), in partnership with collaborators at Colorado State University and Design Impact, is developing the Current/Tidal Optimization (CT-Opt) tool, an open-source, multifidelity, CCD model for HKT conception, design, simulation, and optimization. This tool is based on the Wind Energy with Integrated Servo-control model that was developed by NREL to couple floating offshore wind turbine physical system design with controller design. CT-Opt will leverage the existing frequency-domain Response Amplitudes of Floating



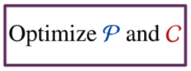
(a) Sequential Design



(b) Iterative Sequential Design



(c) Nested CCD



(d) Simultaneous CCD

FIGURE 1: COMMON INTEGRATED AND CONTROL CO-DESIGN OPTIONS

Turbines (RAFT) and time-domain OpenFAST tools by adding new functionalities that accurately model the physics of HKTs. These lower-fidelity (RAFT) and higher-fidelity (OpenFAST) models will serve as the basis for new, mid-fidelity tools that will enable rapid design iteration and CCD optimization both within and across fidelity levels.

In general, CCD methods seek to optimize the system design and system controller concurrently rather than sequentially or iteratively, as shown in Fig. 1. The goal of the CT-Opt tool is to develop CCD capabilities for simultaneous and nested approaches. By default, CT-Opt will optimize all design variables simultaneously, but multiple instances can be configured to enable nested CCD and sequential approaches. The CT-Opt modeling hierarchy is shown in Fig. 2.

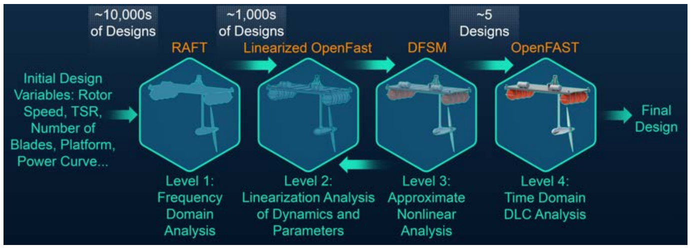


FIGURE 2: CT-OPT MODELING HIERARCHY

Level 1 consists of a frequency-domain analysis, and initial design and optimization work will consider permutations on rotor and platform topology, several different rotor concepts, and control systems, enabling simultaneous CCD. Level 2 will consider additional loads and stability analysis and is included in the CCD problem using the more realistic models generated by linearizing the time-domain nonlinear physics in OpenFAST. A nested CCD strategy will be used in which the outer-loop problem seeks to find the best physical system design; for every candidate physical system description, an inner-loop dynamic optimization problem is solved with respect to open-loop optimal controllers. Level 3 will use a derivative function surrogate model (DFSM) to construct an approximate nonlinear representation of the system behavior. This approach has been shown to be effective on OpenFAST models [4, 5]. With DFSMs that efficiently accommodate plant design changes, both the simultaneous and nested CCD strategies will be possible. At this time, both approaches will be considered, as specific properties of the DFSMs might govern which approach is most effective [4, 6]. A full design load case assessment will be completed in Level 4 with the nonlinear physics-based models of OpenFAST. A closed-loop controller informed by the results of lower levels will be developed for CCD during this phase. At this level of computational expense, running an extensive optimization with hundreds of analysis calls is intractable.

This report summarizes the development plan for CT-Opt, including the addition of HKT capabilities to RAFT and OpenFAST and the development of new linearized and surrogate models. Existing capabilities of RAFT and OpenFAST, in addition to capabilities being actively developed under different projects, are described in Section 2. New capabilities that will be added to each model as part of CT-Opt, the motivation for including these capabilities, and an overview of the modeling approach used to implement them are detailed in Section 3. This section also includes a description of the mid-fidelity models that will be built from RAFT and OpenFAST. Existing and new CCD aspects are summarized in Sections 2 and 3, respectively. Section 4 describes the coupling between individual models and the implementation of CCD across fidelity levels. Section 5 details capabilities that were identified as important for improving model accuracy and flexibility but are not included in the current development plan, and Section 6 presents the conclusions.

2. EXISTING CAPABILITIES

This section describes the existing modeling capabilities of RAFT and OpenFAST, with an emphasis on aspects relevant to HKTs, in addition to capabilities being actively developed under different projects. While both RAFT and OpenFAST serve as the basis for all CT-Opt fidelity levels, RAFT is used most directly in Level 1 and OpenFAST most directly in Level 4. RAFT and OpenFAST will remain independent software packages that can be called by other tools within CT-Opt. The capabilities summarized in this section are either fully implemented or under active development and are distinct from functionalities that will be added as part of CT-Opt.

2.1 RAFT

RAFT (Response Amplitudes of Floating Turbines) is a Python code for frequency-domain analysis of floating wind turbines. As such, it sets up linear, frequency-dependent mass, damping, stiffness, and excitation coefficients for each aspect of a floating wind system and then solves a linear equation of motion to compute the steady-state harmonic response of the system to excitation at each wind or wave frequency. The model incorporates quasi-static mooring reactions, strip theory and potential flow hydrodynamics, blade element momentum aero/hydrodynamics, and linear turbine control. The formulation is compatible with a wide variety of support structure configurations, and no manual or time-domain preprocessing steps are required, making RAFT highly practical in design and optimization workflows. For each load case, RAFT computes frequency-dependent response amplitudes of floating platform motions, nacelle acceleration, tower-base bending moment, blade pitch, mooring line tensions, and rotor speed, torque, and power. RAFT also calculates response amplitude operators, power spectral densities, mean/static properties, and response metrics based on mean and root-mean-square values of each output.

RAFT's existing capabilities include functionalities for modeling floating wind turbines. The mooring system is represented by the quasi-static model MoorPy, which is used to solve mean positions and then linearized to give mooring stiffnesses and tension responses. Dynamic effects and current loads are not included within MoorPy. The floating platform has six rigid-body degrees of freedom and is represented by a collection of cylindrical or rectangular members that can account for internal structure and ballast in the overall mass properties. Hydrodynamics of the floating platform are represented using a strip theory approach that linearizes the relative form of the Morison equation or a linear hydrodynamic implementation using the potential flow preprocessor HAMS. The turbine is modeled as rigid, with lumped rotor mass properties. Rotor aero/hydrodynamics are based on linearized outputs from the blade element momentum solver CCBlade. A linearized, frequency-dependent control capability can interact with the rotor aero/hydrodynamics and mass properties to compute frequency-dependent control action and its effects on the system excitation, damping, and added mass.

Any of the presented integrated design methods (e.g., sequential, simultaneous CCD, or nested CCD) can be used with RAFT because both HKT system and control parameters affect the simulation results. RAFT includes the closed-loop controller when modeling rotor motion, speed, pitch, torque, and thrust to determine the added mass and damping effects caused by the controlled rotor aero/hydrodynamic response. RAFT contains a linear representation of the nonlinear reference controller ROSCO (described in Section 2.2.5). Common gains and set points are used to match the linear dynamic behavior, and nonlinearities are captured by the operating points that vary with inflow speed. More details about the linear control representation can be found in [7].

2.2 OpenFAST

OpenFAST (formerly FAST) is NREL's open-source, physics-based engineering model for whole-turbine simulation [8] and was developed with support from the U.S. Department of Energy. OpenFAST is a modular software composed of a glue code that couples multiple independent modules. Each module simulates a different aspect of turbine operation, such as aerodynamics, structural dynamics, hydrodynamics, mooring dynamics, or controls. The existing OpenFAST architecture for a floating offshore wind turbine is illustrated in Fig. 3. Some modules can be called by their own driver codes (i.e., a code that passes inputs to and receives outputs from a module) to model a single aspect of turbine dynamics, uncoupled from the rest of the code. OpenFAST simulates nonlinear turbine dynamics in the time domain and is therefore the highest-fidelity model included in CT-Opt. The underlying nonlinear equations can also be linearized about operating points to export equivalent linearized state-space models (refer to Section 2.3). The following sections summarize the primary OpenFAST functionalities and highlight capabilities relevant to HKT simulations.

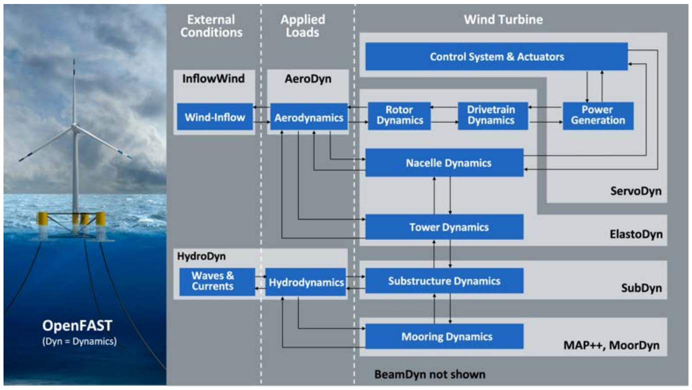


FIGURE 3: EXISTING OPENFAST ARCHITECTURE FOR A FLOATING OFFSHORE WIND TURBINE (FIGURE ADAPTED FROM [9])

2.2.1 Hydrodynamics. For a wind turbine, the rotor aerodynamics and floating substructure hydrodynamics are distinct physical processes that are modeled by distinct modules of OpenFAST. For an HKT, both the rotor and substructure experience hydrodynamic loading, but the rotor and substructure hydrodynamics are still modeled in OpenFAST via distinct modules.

Rotor and tower aero/hydrodynamics are simulated by AeroDyn, which includes submodels to capture rotor wake and induction, blade aero/hydrodynamics, tower dam and shadow, and tower drag effects. When coupled to OpenFAST, AeroDyn is limited to modeling a single axial-flow turbine with two or three blades. The rotor wake and induction effects can be modeled using quasi-steady or dynamic blade element momentum (BEM) theory or a free vortex wake (FVW) model. The BEM models are based on industry-standard theory, with options to capture advanced effects such as high induction, skewed wake, and tip/hub losses through empirical corrections. The dynamic BEM model accounts for time-varying wake and induction effects that result from transient inflow or operating conditions. Because the accuracy of BEM theory is limited by highly skewed flow, curved blades, large blade deflections, or significant rotor motion, an FVW model was implemented to better simulate these complex operating conditions. Additional information on the FVW model is available in [10]. Blade air/hydrofoil aero/hydrodynamics are simulated using either steady or unsteady models. The steady model utilizes user-provided air/hydrofoil lift, drag, and pitching moment coefficients to directly calculate blade loads for a given Reynolds number and angle of attack. The unsteady models calculate corrections to the steady model that account for effects such as unsteady attached flow (Theodorsen theory), flow separation and reattachment, and dynamic stall. The influence of a cylindrical tower on the flow near the blades is captured with potential flow and tower shadow models, and the tower drag is calculated directly from the tower diameter and user-provided drag coefficients.

AeroDyn is being developed to add features necessary for accurately modeling HKTs. The features described in this section are either fully or partially implemented and fall outside the scope of the CT-Opt project. The first HKT-specific capability is a cavitation check. Cavitation on the blades is predicted by comparing the local pressure on the blade surface to the vapor pressure of the fluid. The second HKT-specific capability is the calculation of buoyant loads on the blades, tower, hub, and nacelle. Buoyancy on the blades and tower is calculated by approximating these components as tapered cylinders divided into multiple discrete elements and integrating the hydrostatic pressure over the wetted surfaces of each using an analytical solution developed for cylindrical elements. Since the hub and nacelle are modeled as single points, buoyant loads on these components are estimated based on the volume of fluid that each displaces. Corrections are made to account for the connections between the nacelle and tower top and the hub and blades. The third HKT functionality under active development is the calculation of added mass loads on the blades, tower, hub and nacelle. The added mass loads considered here are caused primarily by hydroelastic structural deformation and/or structure motion. Added mass loads on the blades and tower are calculated by discretizing these components into multiple tapered cylinders with reference volumes based on chord length. Added mass loads are estimated by applying the relative form of Morison's equation to each cylindrical element, given user-provided added mass coefficients. Added mass loads on the hub and nacelle are also calculated by applying Morison's equation and are based on the user-defined volume of each component. Because the hydrodynamic drag loads on the blades, tower, hub, and nacelle are calculated by BEM, FVW, and/or potential flow formulations, the drag and fluid inertia terms in the Morison's equation are ignored. The fourth HKT functionality under development is the calculation of inertial excitation loads caused by flow field accelerations. Morison's equation, including only the inertial term, is applied for this calculation. The final planned HKT capability is to include the effects of flow confinement from the free surface or seabed.

The hydrodynamics of fixed and floating substructures are modeled by HydroDyn. This module calculates hydrodynamic loads using a hybrid combination of potential flow and strip theory solutions. The user must provide coefficients determined from theory, experiments, external simulations, or other means for both models. Loading is induced by regular or irregular waves (that are computed either internally within HydroDyn or externally and supplied as inputs to HydroDyn) and an optional steady current. HydroDyn calculates static buoyancy, added mass, viscous drag, static pressure, fluid inertia, and second-order loads in addition to loads from wave radiation and diffraction, axial loads on tapered members, and member end effects. Internal water ballast can be added as well. HydroDyn can also account for biofouling on the substructure by increasing an element's mass and diameter and using adjusted hydrodynamics coefficients for viscous drag, added mass, and dynamic pressure. The presence of biofouling affects the viscous drag, added mass, fluid inertia, static buoyancy, and gravity loads on the structure.

2.2.2 Structural Dynamics. Structural dynamics of the blades, tower, drivetrain, nacelle, and platform are modeled using ElastoDyn, which is limited to simulating axial-flow turbines with two or three blades. ElastoDyn uses a combination of modal and multibody dynamics. The blades and tower are modeled as flexible members via a modal approach, with small degrees of nonlinearity, that is valid only for moderate deflections. The remaining members are assumed to be rigid and modeled using a multibody dynamics approach that is not restricted to small displacements (except for the floating platform, which allows large translations but only small rotations). To model highly flexible composite blades undergoing large deformations, ElastoDyn's blade model can be replaced by the BeamDyn module. BeamDyn is based on geometrically exact beam theory [11] and can support full geometric nonlinearity, so blade motions are not restricted by moderate deflection assumptions. The structural dynamics of fixed or floating substructures can be analyzed with SubDyn, which models space frame geometries using linear frame finite element beam and Craig-Bampton system reduction models [12, 13]. SubDyn allows for substructure flexibility and calculates loads on individual members. In addition to beams and cantilevered joints, SubDyn also supports rigid links and pretensioned cable elements, as well as pin, universal, and ball joint interconnections. Mooring statics are modeled via the nonlinear analytical quasi-static MAP++ module, and mooring dynamics are modeled via a nonlinear lumped mass approach by MoorDyn or a finite element approach via FEAMooring.

2.2.3 Servo Dynamics. The turbine control system and electrical drive dynamics are modeled by ServoDyn. This module allows the user to select from several standard turbine control options [14], such as active individual or collective blade pitch, active or passive nacelle yaw, variable-speed generator torque, including induction generators, and a high-speed shaft brake. OpenFAST can also simulate active or passive tuned mass dampers and tuned liquid column dampers located within the nacelle, tower, blades, or platform via the Structural Control module within ServoDyn. Active cable tensioning for substructure and stationkeeping control is possible through a ServoDyn coupling to SubDyn and MoorDyn. User-defined, external control algorithms can be implemented through subroutines, dynamic link libraries, or MATLAB/Simulink/LabVIEW interfaces.

2.2.4 Inflow. Fluid inflow on the rotor and tower is handled by the InflowWind module. InflowWind interfaces with the driver code (i.e., the OpenFAST glue code or InflowWind module driver) to pass undisturbed flow velocities at the coordinates specified by the driver at each time step. InflowWind can generate steady flow conditions internally using a power-law fluid shear profile. Inflow conditions can also be specified via externally generated input files. Supported file types include uniform but time-varying inflow, binary full-field turbulence files from NREL's TurbSim turbulence generator or the HAWC aeroelastic turbine simulation code, and binary or native files from DNV's Bladed software. Input files generated by user-defined subroutines are also supported. Internally-generated flow conditions can be used for HKT modeling directly, and TurbSim includes the "TIDAL" spectral model that allows users to simulate turbulence in a tidal channel.

2.2.5 Control Co-Design. Any of the presented integrated design methods (e.g., sequential, simultaneous CCD, or nested CCD) can be used with OpenFAST because both HKT system and control parameters affect the simulation results. However, since the computational effort of optimizing control parameters is the same as optimizing HKT parameters (i.e., OpenFAST simulations must be run), a simultaneous CCD approach is recommended. A closed-loop controller (e.g., ROSCO [15]), can be coupled with OpenFAST to compute simulation-based outputs such as power and fatigue and extreme loading. These outputs can be used in structural design models to compute design constraints and costs. Any closed-loop controller could be used, but a framework for ROSCO is provided. ROSCO can be tuned for a variety of turbines and goals, leading to many CCD options.

2.3 Linearized OpenFAST

The linearization functionality of OpenFAST enables linearization of the underlying nonlinear equations about an operating point. This involves calculating the Jacobians of the state derivates and outputs with respect to the states and inputs. The linearization process involves: (1) finding an operating point; (2) linearizing the underlying nonlinear equations of each module about the operating point; (3) linearizing the module-to-module input-output coupling relationships in the OpenFAST glue code about the operating point; (4) global assembly of all Jacobians into the full-system state matrix, the input matrix, the state matrix for outputs, and the input-transmission matrix for outputs; and (5) exporting the matrices and operating point as outputs. Once generated, the linearized model is valid for small deviations (i.e., perturbations) from the operating point. Linearization is often advantageous to understanding the system response and exploiting well-established methods and tools for analyzing linear systems. For example, linear state-space models can be transformed to transfer functions, impulse-response functions, or frequency-response functions. The ability to generate linearized models is important for eigenanalysis (to derive structural natural frequencies, damping ratios, and mode shapes), controls design (based on linear state-space models), stability analysis, gradients for optimization problems, and support for the development of reduced-order models.

3. CT-OPT FUNCTIONAL REQUIREMENTS

This section describes the functionalities that will be added to RAFT and OpenFAST as part of the CT-Opt project. These functionalities were identified by the NREL team and collaborators with feedback from an external advisory board composed of members from academia, industry, and government. Details of the mid-fidelity models based on RAFT and OpenFAST and CCD aspects of CT-Opt are also given.

3.1 RAFT

Functional requirements for RAFT beyond its existing capabilities are focused on supporting HKT rotors and accounting for current loads on the structure. The most important additions for the rotor are to model added mass forces occurring in reaction to rotor accelerations and inertial excitation loads caused by accelerations of the flow field. These phenomena will be included by capturing their effects on the axial force and rotational moment of the rotor in a spatially averaged sense. Support for combining current and wave velocities and accelerations to calculate rotor-averaged inflow spectra will also be required. Minor additional capabilities will be added to model buoyancy on the rotor, flow confinement effects (from free surface, seabed, or multiple rotors), multirotor designs, and cavitation.

To account for current loads on the structure, RAFT will need to include a new constant term in its strip theory calculation of drag on the substructure. This will be similar to existing drag calculations but will be a mean rather than dynamic load. Potentially significant drag loads on the mooring system also need to be accounted for using a quasi-dynamic rather than quasi-static mooring modeling approach. This will allow calculation of mean current loads and linearized drag and added mass effects on the mooring system. It will also provide a more accurate prediction of dynamic mooring line tensions.

3.2 OpenFAST

Similar to RAFT, new functional requirements for OpenFAST are focused on supporting HKT rotors and accounting for wave and current loads on the entire system. It should be noted that new functionalities pertain only to axial-flow HKT geometries. The updated OpenFAST architecture for HKTs is illustrated in Fig. 4.

OpenFAST was originally developed for wind turbines and assumes the rotor-nacelle assembly and tower are above ground for land-based turbines or above the mean sea level (MSL) for offshore turbines. Therefore, most modules (e.g., AeroDyn,

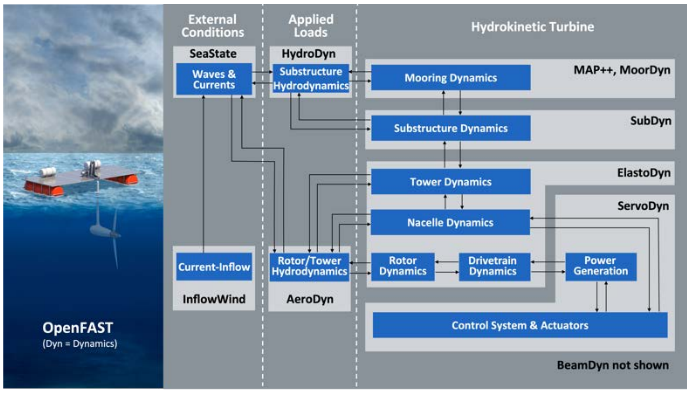


FIGURE 4: UPDATED OPENFAST ARCHITECTURE FOR HKTs (FIGURE ADAPTED FROM [9])

ElastoDyn, InflowWind, and TurbSim) are limited by this assumption and cannot model turbines with a rotor-nacelle assembly and tower below the MSL, such as fixed and floating HKTs. To model these geometries, OpenFAST will be modified such that modules allow the definition of a rotor-nacelle assembly and tower below the MSL. This will involve modifying specific geometry checks, adjusting inflow coordinates, and updating depth-based calculations in AeroDyn.

OpenFAST will also be modified to model the more generalized tower and support structure geometries common in HKT systems. To calculate the hydrodynamic loads on these structures while still accounting for their interactions with the rotor, AeroDyn will be updated to include hydrodynamic loads on elliptical towers via a potential flow solution. This solution will include the ability to model double-sided and angled towers. This will enable the hydrodynamics of simple tower components to be modeled in AeroDyn, while multibody, large-volume, and surface-piercing structures will continue to be modeled in HydroDyn. Note that this will limit the geometry of support structure components interacting with the rotor to single-member cylindrical or elliptical towers. Lift forces acting on faired components will be considered as well. OpenFAST currently assumes that the interface between the tower and substructure (i.e., between the components modeled by AeroDyn and HydroDyn) is located above the MSL, where fluid loads on the substructure are neglected. Since this interface will likely occur below the MSL for HKTs, its influence on the fluid loading experienced by the structures modeled in both AeroDyn and HydroDyn will need to be captured. Fluid loads on any surface-piercing parts of the tower or support structure are currently neglected.

In addition to the added mass forces caused by hydroelastic structural deformation and/or structure motion detailed in Section 2.2.1, added mass loads due to blade pitch accelerations that occur while the turbine is operating under pitch control will also be added. Like the added mass forces calculated for each blade section, the pitch-induced added mass moments are based on the Morison equation with the inertia term neglected.

As described in Section 2.2.1, inertial excitation loads on the HKT system caused by flow field accelerations are being added to OpenFAST under a different project. To calculate these loads, inflow accelerations must be provided by InflowWind. To enable accelerations to be calculated regardless of the origin of the flow field information, a numerical differentiation or curve-fitting approach will be applied to velocities after they are read in by InflowWind.

The final HKT functionality that will be added to OpenFAST is the coupling of wave and current velocities in the inflow. A simple superposition approach will be used initially, and a more realistic coupling model [16] will be added in future releases. This coupling will be able to capture regular or irregular waves traveling in a steady, uniform or nonuniform current and regular or irregular waves propagating from an area with no current to an area with a steady, uniform or nonuniform current.

3.3 Linearized OpenFAST

The physics-based improvements to OpenFAST outlined in Section 3.2 will be linearized where appropriate and included in linearized state-space matrices output from OpenFAST. The calculation process for arriving at operating points will be unchanged. The new physics added to the AeroDyn and HydroDyn modules will be included in the module-level Jacobians. Updates to the module-level interactions will be reflected in the module-to-module input-output coupling relationship as well as the full-system state-space matrices. The end result will be the ability to extract from OpenFAST linearized physics-based representations of fixed and floating HKTs.

3.4 Derivative Function Surrogate Model

Identifying the optimal design via a time-domain study for HKTs may require several hundred OpenFAST calls to determine the system response. Because of the complicated nature of HKT dynamics, a single OpenFAST call is on the order of several minutes. Therefore, direct OpenFAST calls can be computationally intractable for an optimization-based design study. A surrogate model (SM) is an attractive option to approximate the system response from a complex function such as OpenFAST. Traditionally, SMs are developed as computationally inexpensive black-box functions that capture system input-output relations. The applicability of SMs to optimization-based design studies has been thoroughly established [17, 18].

When designing a dynamic system, the evolution of the system states is an important consideration, and many traditional SM approaches do not capture such information. For example, open-loop optimal control-based CCD studies using direct transcription are a popular option for establishing the maximum achievable performance of a system [19]. For these direct transcription-based studies, the dynamic model or derivative function is necessary to optimize how the system states evolve, and such information is not directly or cheaply available through OpenFAST. Even for closed-loop control simulations and optimization, an inexpensive yet accurate dynamic response calculation would be quite valuable. The traditional input-output mapping approach should be modified to use surrogate modeling for dynamic systems like HKTs [20, 21]. A DFSM is an SM of the state derivative functions (and outputs) of the given system, as shown in Fig. 5. A DFSM captures the potential continuous evolution of the system states and outputs through an inexpensive black-box SM [4]. When using DFSM at Level 3 or linear models at Level 2, where the different quantities captured by the low-fidelity models are the independent variables for the system, constraints can be placed directly on these quantities as part of the optimization problem formulation. For example, in [19] the authors place different constraints on the controls and state variables associated with the system. Simulations with this DFSM can be 1,000 times faster than a direct OpenFAST simulation.

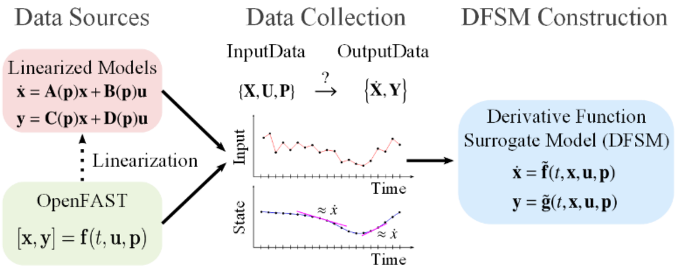


FIGURE 5: CONSTRUCTION OF A DERIVATIVE FUNCTION SURROGATE MODEL

Linearized dynamic models of an underlying nonlinear process, such as those described in Section 3.3, are a type of DFSM because they constitute an approximate mathematical model of the state derivatives. The main issue with these models is that they are only accurate near the operating points they were constructed at and can be sensitive in certain regions. For nonlinear systems such as HKTs, this is not sufficient for simulation and design studies that require exploring the entire state space. Furthermore, the construction of the linearized models is often quite expensive [22], even though the eventual product is extremely fast to evaluate (and similar in expected cost to the DFSMs). Finally, CCD studies necessitate derivative models that can efficiently represent plant variable changes (e.g., if a turbine blade length is changed). Therefore, CCD design studies only using linearization capabilities can be inefficient.

Therefore, we will construct DFSMs from OpenFAST data. If the given simulation covers the entire working region, then a single simulation could be sufficient to build an accurate DFSM. Thus, a DFSM depends less on an operating point than a linearized model. Also, the linearized models from Level 2 can be used to directly provide derivative data and accuracy comparisons, as was done in [4]. Finally, by sampling different plant designs, a single DFSM can be constructed to support CCD studies naturally and efficiently. Once a suitable DFSM is constructed, it will be available to support different control and CCD studies.

With this context, the following requirements are established for the DFSM module in CT-Opt:

- A valid DFSM shall support plant design changes commensurate with OpenFAST capabilities.
- A valid DFSM shall predict state derivatives and outputs given current states and inputs (disturbances, plant variables, etc.) within an acceptable tolerance when compared to the ground truth OpenFAST simulations. This will require the incorporation of linearized and direct simulation data from OpenFAST.
- A valid DFSM shall be fast to evaluate (i.e., the closer to linear model evaluation times, the better).
- A valid DFSM shall integrate with the dynamic optimization tool for CCD using optimal open-loop control.
- The overall DFSM-based CCD methodology shall be cost-effective compared to Level 4 and more accurate than Level 2.
- The DFSM module shall support strategies for exploring the state space for data collection purposes. This might include a controller that tries to move around the state space rather than maximizing power or customized design load cases that promote such exploration.

4. CT-OPT INTEGRATION

CT-Opt integration can be categorized into three main topics: 1) User Experience, 2) Integration, and 3) Optimization and Numerics. User experience requirements involve a common geometry parameterization of the turbine and support structure, a graphical user interface (GUI) with a system visualization for the numerous user inputs, and documentation with examples. Integration requirements include establishing a single driver with variable passing for all CT-Opt modules, the inclusion of pre- and postprocessing tools, and a global load case driver. Finally, the optimization and numerics requirements involve implementing the multifidelity and CCD techniques developed for CT-Opt and adding OpenMDAO extensions for other external optimization and uncertainty quantification libraries. It is critical that multifidelity management methods are carefully developed to facilitate the passing of CCD optimized solutions back and forth between model fidelity levels.

To run CT-Opt, a user must provide an initial geometry parameterization. Examples will be provided in the repository. Modeling inputs define how the HKT is simulated, and analysis inputs determine whether optimization, parameter studies, or single runs are performed.

4.1 User Experience

4.1.1 Common Geometry Parameterization. Turbine and support structure designers will need to describe their specific design geometry and control actuator details in CT-Opt. CT-Opt will provide users with a geometry parameterization broad enough to capture numerous different approaches, while being specific enough for detailed design trade-offs. A YAML file will capture the ontology in a human-readable and computer-parsable format.

4.1.2 GUI with Turbine and Support Structure Visualization. CT-Opt will include a GUI to facilitate rapidly navigating its many inputs and to assist designers in learning the co-design capabilities of the toolset. The GUI will enable users to

- Set environment variables and select design load cases
- Select fidelity levels to be evaluated as well as select modules in each fidelity level
- Set input variables for each module
- Select the optimization library and drivers
- Specify design variable, as well as constraints and objective functions.

4.1.3 Documentation and Tutorials for Users. CT-Opt will offer users many capabilities and "knobs" to turn. Documentation and tutorials will enable user success with CT-Opt. The documentation and tutorial sets will include

- Sample inputs for simple and advanced MHK turbines and support geometries
- Sample inputs for a full set of design load cases, to enable CCD optimizations across the full range of model fidelity levels in CT-Opt
- Sample inputs for a narrower set of CCD optimizations focused on a single model fidelity level with module-specific analyses at that level
- A stand-alone theory guide for all modules (stretch goal).

4.2 Integration

4.2.1 Python Driver for All Modules with Common Variable Sharing. CT-Opt will offer users a single gateway to leverage all modules to conduct co-design optimization. To facilitate rapid optimization and multifidelity transitions, all CT-Opt modules will be able to share variables and Jacobian data directly. This will eliminate the need for intermediate input/output text files that would slow down optimization, enabling seamless passing of chain rule partial derivatives back to the optimization driver.

4.2.2 Pre- and Postprocessing Tools. Various pre- and postprocessors need to be incorporated into CT-Opt so that design optimization can link geometry to objective functions and constraints. Example preprocessors include hydrofoil preparation data for BEM solvers, simple cross-sectional composite property models, and structural mode-shape solvers. Examples of postprocessors include scripts to determine extreme loads and events and determination of fatigue events and limits.

4.2.3 Global Design Load Case Driver. A common description of the meteorological and ocean/tidal environment will be used for all fidelity levels in CT-Opt. Consistent wind/wave/current conditions for use in the frequency and time domains will be specified. For Level 1, linear inflow with spectral turbulence parameters will be specified, along with frequency domain descriptions of currents and spectral models for irregular waves. The full time-domain design load case set will be available for nonlinear analysis at Levels 3 and 4.

4.3 Optimization and Numerics

4.3.1 Multifidelity Model Management Strategies. At each model fidelity level, the CCD optimization methods will be integrated into the frequency domain, linear time domain, and nonlinear time domain. The transitions between fidelity levels offer an opportunity to conduct a more thorough and rigorous optimization. For example, CCD solutions determined at Level 1 must be able to be passed to higher levels for further detailed CCD optimization. If a solution determined at the higher fidelity levels is deemed infeasible, it must be passed back to lower fidelity levels to obtain a feasible solution. To enable this capability, a multifidelity model management strategy will be customized and implemented for the different fidelity transitions in CT-Opt, using a trust region approach. CT-Opt users will also be able to run a model fidelity tier independently from the other tiers and manually direct a transition from one tier to another.

4.3.2 Extensions for Additional Optimization and Analysis Libraries. CCD optimization could require sophisticated optimization algorithms to yield cost effective designs for systems with highly coupled dynamics. Conceptual design optimization that surveys different architectures and topologies would require mixed-integer optimization studies. It might also include developing uncertainty descriptions to enable optimization under uncertainty. Candidate optimization packages offering unique capabilities include NLopt [23] and Dakota [24].

5. LOWER-PRIORITY FUNCTIONAL REQUIREMENTS

This section describes modeling capabilities that would increase the accuracy of HKT simulations and add flexibility to the models but are outside of the current scope of work. These lower priority functional requirements are left as suggestions for future work.

5.1 RAFT

A range of additional functional requirements would be of interest for future work with RAFT. Other HKT topologies could potentially be modeled, ranging from cross-flow rotors to oscillating hydrofoils and kite devices. Rotor modeling could be improved to account for the tower influence, improve the calculation of blockage effects, and model out-of-plane hydrodynamic moments and reactions. For the structure, modeling lifting loads on foil-shaped members could better represent some designs. Support for single-point and turret moorings could be added, as well as analyzing the device ability to transition across different loading directions. Structural control capabilities would enable more advanced control co-design studies. Lastly, modeling the effects of biofouling could be relevant on all parts of the system, from performance degradation of the rotor to additional weight and drag on the substructure and mooring lines.

5.2 OpenFAST

As mentioned earlier, the CT-Opt project is focused on axial-flow HKT geometries. Other turbine types, including cross-flow, oscillating hydrofoil, ducted or enclosed tip, Archimedes screw, and kite geometries [25] could be considered in the future. There are several additional capabilities not considered in the current functional requirements that could improve the accuracy of the OpenFAST model for HKTs. These include improving the structural model to enable fully coupled simulations of multiple rotors on a single platform, accounting for flow confinement effects from multiple rotors, modeling biofouling on turbine blades, capturing the influence of cavitation on the hydrodynamic models, and updating the aeroacoustics module to work under water, including capturing the effects of cavitation on acoustics. Additional improvements to the substructure could include modeling hydrodynamic lifting loads and unsteady vortex-induced vibrations in HydroDyn in addition to allowing members with noncylindrical cross sections. Additionally, the mooring modules (i.e., MAP++, MoorDyn, FEAMooring) could be improved to account for biofouling on the mooring lines. The capability to model a platform moored by single-point and turret moorings could be added, as could the analysis of device ability to transition across different loading directions. Finally, additional options for near-surface current profiles could be added.

5.3 Surrogate Model

There are many potential options for constructing the DFSM and sampling strategies to get the required data. These options will be evaluated throughout the natural development of the DFSM methodology for CT-Opt. The immediate goal is a single good recommendation and implementation in CT-Opt, but alternative surrogate modeling methods and sampling strategies may be supported as well to support broader CCD activities that leverage DFSM.

DFSMs may have alternative use cases in CT-Opt beyond use in Level 3 CCD studies. This might include leveraging the approximate derivative functions for closed-loop control simulations and linearized model creation.

6. CONCLUSION

CT-Opt is a control co-design modeling tool for marine hydrokinetic turbines being developed by NREL and collaborators at Colorado State University and Design Impact. This tool will enable the design and optimization of HKTs at and across multiple fidelity levels. The lowest-fidelity (Level 1) model will be based on RAFT, a frequency-domain model developed to predict the response amplitudes of floating offshore wind turbines. Similarly, the highest-fidelity (Level 4) model will be based on OpenFAST, a time-domain model that can simulate the nonlinear aero-hydro-servo-elastic response of land-based and offshore wind turbines. Capabilities to support HKT rotors and account for wave and current loads on the system will be added to both RAFT and OpenFAST to enable them to accurately simulate fixed and floating HKT systems. Two mid-fidelity models will also be developed for CT-Opt. These Level 2 and 3 models will be based primarily on OpenFAST and designed to improve upon the accuracy of Level 1 while providing more computationally efficient solutions than Level 4. The linearized OpenFAST (Level 2) model will be produced by linearizing the fully coupled, nonlinear equations about specific operating points. The DFSM (Level 3) model will approximate the nonlinear system behavior and will be based on linear and nonlinear OpenFAST results. To produce robust, cost-effective designs, optimization schemes will use control co-design methods that enable coupled optimization of the system design and control variables. Control co-design optimization will be possible both within individual models and across fidelity levels. The individual models will be integrated to enable efficient simulations at multiple fidelities. Integration work consists of improving the user experience through common geometry parameterization, development of a graphical user interface for model inputs, and publication of documentation, including tutorials and examples. Integration will also involve development of a common driver for all modules, inclusion of pre- and postprocessing tools, and common descriptions of environmental conditions.

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