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GENETIC ALGORITHM-BASED PLATFORM OPTIMIZATION FOR FLOATING OFFSHORE WIND TURBINES

Matthew Hall, Brad Buckham, Curran Crawford
Department of Mechanical Engineering, University of Victoria
PO Box 1700, Stn. CSC, Victoria, BC, V8W 2Y2, Canada
mtjhall@uvic.ca, bbuckham@uvic.ca, curranc@uvic.ca

ABSTRACT

A global optimization tool has been developed that enables identification and evaluation of optimal support structure configurations for floating offshore wind turbines. Floating support structures have the potential to dramatically expand the domain of the offshore wind energy industry by providing access to deep-water sites that are out of reach of conventional bottom-fixed support structures. The technology is young, and the complex floating platform design problem inhibits a convergence of designs. Researchers have tried using geometry parameterization techniques to identify optimal points in the floating platform design space. However, these past efforts have been limited in breadth, suffering from parameterizations that exclude a number of important design options. The present work explores the floating platform design space more fully by applying a flexible, genetic algorithm-based optimization framework. Judiciously-selected decision variables drive a geometry model that supports a diverse range of floating platform configurations and an accompanying mass model that features intelligent ballast distribution. The panel method code WAMIT, supplemented by a custom viscous drag model, provides platform hydrodynamic characteristics. A coupled frequency-domain floating wind turbine model is used to evaluate the system dynamics, which in turn inform the objective function. The exploratory design optimization made possible by this framework is shown to yield a set of distinct locally-optimal designs – some that are similar to well-established spar and semi-submersible configurations, and some that are less conventional. This broader exploration of the design space is therefore useful in both verifying the optimality of existing design concepts and identifying promising configurations that lie outside existing intuition-guided design concepts.

INTRODUCTION

As the fledgling floating wind turbine industry gets its feet wet, with several MW-scale prototypes now in the water, convergence to a single optimal support structure configuration has not yet occurred. The overall goal of the support structure is to provide a stable base for the wind turbine. The problem is the sheer complexity of the support structure design problem – a design problem characterized by significant technical challenges, conflicting design objectives, and myriad configuration possibilities. As well, different sites with different weather conditions and water depths will yield different optimal configurations. Clouding the issue is the difficulty in solving the design problem by computational means; the modelling tools rely on sometimes-tenuous assumptions, the computational expense of parametrically evaluating the full range of possible designs is astronomical, and optimization studies have thus far tended to exclude important parts of the design space. As a result, research attention remains divided across a variety of support structure configurations and there exists the possibility that promising configurations lie waiting in unexplored regions of the design space.

The present work provides a new design space exploration tool that aims to shed light on the optimal configuration issue. This is done using a genetic algorithm-based optimization framework that features a more flexible geometry parameterization and more advanced dynamics model than any previous global optimization attempts in the literature. Judiciously-selected decision variables drive a geometry model that supports a diverse range of floating support structure configurations. The panel method code WAMIT, supplemented by a custom viscous drag model, provides platform hydrodynamic characteristics, while a quasi-static mooring line model provides linearized mooring forces. The floating wind turbine code FAST provides linearized wind turbine effects. A frequency-domain model couples these inputs together and evaluates the system response in the six platform degrees of freedom (DOFs), which in turn informs the objective function.

The goal of this tool is not to automate the design process - the design problem is too complex and multifaceted for that. Rather, the intention is to provide a framework that can be applied to a given siting scenario to produce a list of all the reasonable locally-optimal floating support structure configurations, as a starting point for more conventional design processes. This way, more conventional design approaches (and optimization algorithms) will converge to optimal designs faster, and promising design options will not be overlooked for lack of adequate parameterisation. As well, the framework may well lead to more general insights into the design problem.

Parameterizing the Design Space

Parametric optimization, the standard approach for determining an optimal floating platform shape, represents the platform geometry by a number of parameters that become decision variables in the optimization. Unfortunately, the simplicity gained by reducing the design problem to a small set of continuous decision variables (in order to suit gradient-based optimization methods) comes at the expense of limited design flexibility. This approach is well-suited to sizing existing configurations but can be limiting when it comes to exploring different configurations.

Sclavounos, Tracy, and Lee (2007) conducted a parameter study using a relatively flexible geometry parameterization and frequency-domain modelling to find Pareto-optimal support structure designs. Their model used a cylindrical platform of variable dimensions and mooring lines of variable tension and angle to span all three stability classes, from TLPs to spar-buoys to cylindrical barges. Although their parameterization supported an impressive array of options, its limitation to a single cylinder excluded multi-cylinder configurations, an important part of the design space given the recent trends toward tri-floater platforms. Parameterizing such a complex design problem runs the risk of artificially limiting the design space and consequently constraining the creative process. Comparison studies have also been done on sets of existing designs (eg. Jonkman and Matha, 2011; Robertson and Jonkman, 2011) but these studies, while highly accurate and useful in comparing already-established designs, lack the ability to explore the design space. In an attempt to sidestep the limitations of geometry parameterization approaches while still exploring the design space, a so-called “performance-based” optimization approach using a basis function analogy to blend the performance characteristics of different “basis” platform designs was previously attempted (Hall, Crawford, and Buckham, 2012). While an informative exercise, serious obstacles were encountered in its maintaining consistency with physically-plausible results.

To provide a truly global optimization framework for the support structure, a parameterization that captures the full range of the design space is required. For a geometry-based optimization, this means that any existing design geometries, as well as any reasonable newly-conceived ones, must be able to be recreated by the parameterization scheme. Creating a scheme that meets those requirements is one challenge, as is integrating modelling techniques to evaluate the designs created by the scheme. Another challenge is creating the framework that the scheme operates in; the many discontinuities in the design space (from different numbers of floats, vastly-different configurations, etc.) and potential for many local optima require careful arrangement of the decision variables to provide a well-organized design space and an optimization algorithm designed to handle discontinuities and multiple optima. A framework that attempts to meet these challenges is presented here.

THE FRAMEWORK

The framework and its exploration of the design space are controlled by a custom genetic algorithm (GA). With the expectation of finding multiple local optima, and the diverse, interrelated, and often-discontinuous decision variables involved, a genetic algorithm-based optimization scheme was selected as the most flexible and straightforward way to programmatically explore the design space.

The algorithm for this framework has two goals that are not common for all GAs: use as few function evaluations as possible and be able to identify and converge to multiple local optima. Because the evaluation of each individual design (and the hydrodynamic analysis in particular) is vastly more time consuming than the operations of the GA itself, the algorithm is designed to limit redundant or unproductive fitness function evaluations. With the possibility of multiple local optima, the algorithm is also designed to support multi-niching – the ability to converge to multiple optima simultaneously. Recognizing that the limited fidelity of a frequency-domain model may create distortions in the design space and that additional factors not included in the framework also affect the choice of optimal design, a novel multi-niching technique inspired in part by the work of Cedeño (1995) was developed to explore local optima in an equitable way, regardless of their comparative fitness values, so that potentially promising configurations are not unfairly discriminated against. Confirming with certainty which local optima is the global optimum is then left to higher-fidelity time-domain simulation tools, which are necessary in any case for verifying, fine-tuning, and elaborating on the optimization results.

Platform Geometry Scheme

The heart of the optimization framework is the platform geometry description scheme. In the interests of optimization simplicity, the scheme has the objective of describing the widest range of feasible platform configurations with as few decision variables as possible. Additionally, preserving some degree of continuity or consistency in the effects of the decision variables across their ranges and avoiding any redundancy (in which similar configurations could be achieved by different combinations of decision variables) is important in order to keep the design space organized. Adhering to these objectives speeds up GA convergence and makes results easier to interpret.

A geometry scheme based on vertical cylinders was selected to parameterize the platform geometry. This is the most straightforward option considering the range of existing platform designs and the preference for cylindrical hulls for hydrodynamic, structural, and manufacturing reasons. The scheme consists of a central cylinder whose radius and draft are variable, with the additional control of a variable amount of taper at the water plane, and an array of three or more outer cylinders whose radius, draft, and distance from the center are collectively variable. The outer cylinders can feature circular heave plates of variable sizes at their bases. The inner cylinder or the outer cylinders can be excluded by using a minimum threshold in their radius decision variables. This is an example of implementing a discontinuous feature in an intuitive way in a continuous decision variable, though a gradient-based optimizer would still be challenged by this scheme. The geometry scheme is illustrated in Fig. 1 and the decision variables are listed in Table 1.

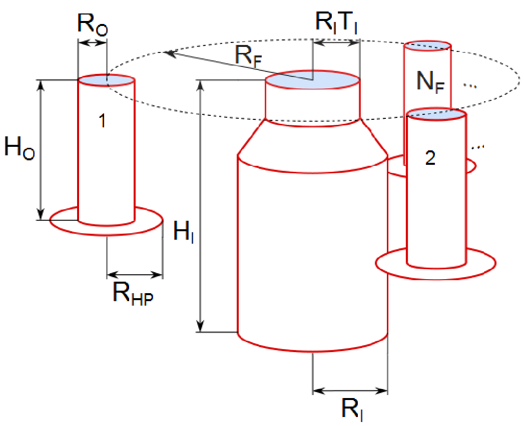

Fig. 1. Platform Geometry Scheme

Table 1. Platform Geometry Decision Variables.

Variable	*Description*
H_I	Inner cylinder draft
R_I	Inner cylinder radius*
T_I	Inner cylinder top taper ratio
N_F	Number of outer cylinders
R_F	Radius of outer cylinder array
H_O	Outer cylinders draft
R_O	Outer cylinders radii**
R_{HP}	Outer cylinders heave plate radii***

* below threshold disables inner cylinder
** below threshold disables outer cylinders
*** below R_O disables heave plates

Mooring Configuration Scheme

Mooring systems for floating wind turbines conventionally fall into one of two distinct configuration types - slack catenary lines or taut vertical lines - with variations within these configurations in the number of lines, the fairlead and anchor locations, and the line lengths (or equivalently tensions). For the sake of flexibility, the mooring configuration scheme was designed to support variations in catenary and taut line configurations, but also support intermediate configurations. The mooring line configuration in the framework is determined by one dedicated decision variable in conjunction with several of the platform geometry decision variables and water depth. The dedicated mooring decision variable, x_M, controls a mooring configuration algorithm that transitions smoothly between a taut vertical TLP configuration and a slack catenary configuration with widely-spaced anchors, as illustrated in Fig. 2. This technique was selected in order to avoid wasting computation time on impractical mooring configurations. The number of mooring lines and the fairlead locations are determined by the platform geometry and x_M. If there are multiple cylinders, the number of lines is equal to the number of outer cylinders and the fairleads are at the outer edge of the bottom of each of the outer cylinders. If there is only one central cylinder, three lines are used and they connect at the bottom circumference for a taut mooring system and half way along the draft for a slack mooring system. The anchor locations are determined by the mooring decision variable and vary linearly with x_M from lying directly under the fairleads (at x_M=0) to having a horizontal spread of double the water depth (at x_M=2). In this work, “slack” implies that portions of the mooring lines rest on the sea floor, hence the only vertical force imparted to the platform by the mooring lines is from their weight. “Taut” implies that no part of the mooring lines lie on the sea floor, meaning the vertical force on the platform comes from both the weight of the mooring lines and their pretension. The mooring configuration algorithm is set up such that the transition between taut and slack configurations occurs at x_M=1, corresponding to anchors spaced a horizontal distance from the platform equal to the water depth. The mooring line tension is determined by the mooring configuration algorithm for slack catenary configurations but for taut configurations the tension is adjusted so that there is no surplus buoyancy in the system (i.e. it is a function of the platform decision variables) and no ballast in the platform is assumed. At present, the mooring line material properties and diameters are kept fixed.

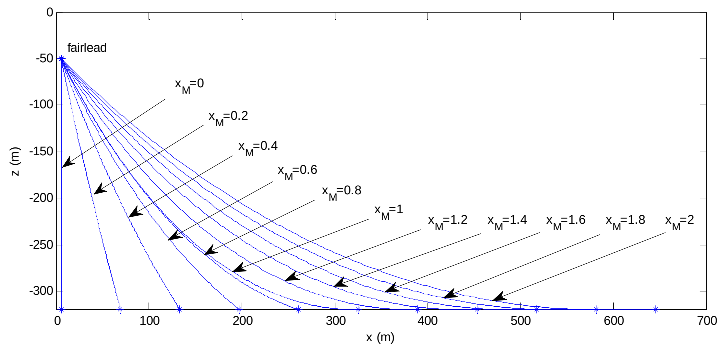

Fig. 2. Example of possible mooring line configurations controlled by x_M.

Platform Mass and Ballast Scheme

The platform geometry scheme and mooring configuration scheme go hand-in-hand with a mass model that predicts the mass characteristics of the platform and decides on the use of ballast. The distributed mass of the platform is modelled by assuming constant-thickness structural steel on the surface of the platform, including the heave plates. This thickness is greater than that of physical designs to also represent the mass of structural elements (bulkheads, stiffeners, stringers, etc.) within the platform.

The mass of required structural elements connecting multiple cylinders is also modelled, as a necessity for representing the expense of widely-spaced cylinders. The model estimates the mass of the connective structure to be a linear function of cylinder spacing. The number of cylinders is chosen to not affect the mass because the size of the cylinders and hence their loads will vary inversely with their number. The linear constant applied in the model represents the cross sectional area (or equivalently the linear density) of the connective members. For rotational inertia calculations, it is assumed that the connective members are uniform beams running from the center of each outer cylinder to the center of the platform. One beam is at the waterline and one is at the outer cylinder draft.

The ballast mass is set according to the surplus buoyancy of the system – the remaining buoyancy force after subtracting wind turbine weight, platform structure weight, and the vertical component of mooring line tensions. In the case of taut mooring line configurations, no ballast is applied and instead any surplus buoyancy is left to be taken up by increasing the mooring system tension.

Objective Function and Constraints

Support structure performance is primarily concerned with the minimization of motion-induced loads on the wind turbine. The wind turbine loads most affected by support platform motion are blade root flapwise bending moment and tower base fore-aft bending moment. Both are closely linked to platform surge and pitch motions. Blade root flapwise bending has the potential to be the most critical point of failure because of the higher natural frequencies and flexibility of the blades. The dominant driver of blade flapwise bending loads in a floating system is nacelle fore-aft acceleration; therefore this is used for the objective function. With the small angle assumptions inherent in the linear analysis, the nacelle fore-aft acceleration is (Tracy, 2007):

$$\mathrm{RAO}_{\mathrm{a\ nacelle}}(\omega) = -\omega^2 \left(\mathrm{RAO}_1(\omega) + \mathrm{h}_{\mathrm{nacelle}} \mathrm{RAO}_5(\omega) \right) \quad (1)$$

where $h_{nacelle}$ is the height of the nacelle, RAO is a complex response amplitude operator (conveying both the amplitude and the phase of the response in the frequency domain) and the numerical subscripts denote the platform DOFs (1=surge, 5=pitch). Applying a wave spectrum, the root-mean-square nacelle acceleration, $\sigma_{a\ nacelle}$, in the wave conditions described by wave power spectral density $S(\omega)$ can be calculated as:

$$\sigma^2_{\mathrm{a\ nacelle}} = \int \left| \mathrm{RAO}_{\mathrm{a\ nacelle}}(\omega) \right|^2 S(\omega) d\omega \quad (2)$$

The choice of Eq. (2) for the objective function focuses the optimization on providing a stable platform that will be most suited to supporting turbines of a conventional strength and construction, which will lower costs and increase feasibility as far as the wind turbine is concerned. Complexities and uncertainties involved in estimating cost of energy are avoided by applying constraints on the support structure that are designed to limit the overall support structure expense to a common but unspecified value. The optimization is thus framed so as to find the most stable support structure design given a fixed budget.

The overall expense of the system is capped by placing a constraint on the sum of the weight of the platform structure (excluding ballast) and the vertical force caused by the tension of the mooring lines. The rationale is that the main cost factors are the mass of the platform structure and the tension in the mooring lines. This is similar to the total displacement approach taken by Sclavounos et al. (2007), except the approach here does not count the mass of the ballast, which for the inexpensive concrete being considered is appropriate. When this structural expense constraint is combined with a minimum net buoyancy constraint reflecting the need to support the weight of the turbine, there are now effective upper and lower bounds on the size of the platform. An upper bound on mooring line tensions for taut mooring configurations falls out of this approach as well.

The frequency-domain modelling approach for the combined system means that the static posture of the system needs to be evaluated separately. The mooring systems in the design space will all provide adequate station keeping against the thrust force of the wind turbine. However, the static pitch angle of the platform is not inherently guaranteed to be within reasonable limits. A constraint was therefore added to keep the static pitch to within 5°, a widely-used limit for floating wind turbines. However, realizing that buoyancy-stabilized designs such as the WindFloat can be designed to make use of active ballast shifting to further reduce static pitching, this constraint is relaxed to 10° for configurations with multiple cylinders.

The support structure stiffness in pitch is a function of the platform volume, V, and center of buoyancy, h_{CB}; the overall structure mass, M, and center of mass, h_{CM}; the water plane moment of inertia, $I_{xx,WP}$; and the mooring system stiffness in pitch $C_{mooring,5,5}$:

$$C_{5,5} = -\rho_w V g h_{CB} + M g h_{CM} + \rho_w g I_{xx,WP} - C_{mooring,5,5} \quad (3)$$

Multiplying the maximum thrust force of the wind turbine by its hub height provides the peak overturning pitch moment that can be expected. From this, the required overall stiffness to limit the maximum pitch to an acceptable value can be calculated, remembering that Eq. (3), like the rest of the model, assumes small angles.

Inputs

Interwoven with the geometry, mooring, and mass schemes are a number of parameters related to assumptions about the platform construction and the constraints on the design problem. These include the hull thickness, ballast density, and connective member linear density used in the mass model; the mooring line size, weight, and stiffness used in the mooring model; and the minimum net buoyancy requirements, maximum acceptable static pitch angles, and maximum combined structural weight and mooring system vertical tension in the constrain equations. For the optimizations presented here, values for these constants were selected through careful comparison to the two standardized floating wind turbine designs created for the International Energy Agency's IEA Wind comparison efforts: the OC3 Hywind (Jonkman, 2010) and the OC4 WindFloat (Roddier et al., 2011). An effort was made to calibrate the parameter values to replicate these two designs, and adjust the constraints to include these designs but exclude designs that are expected to be significantly more structurally-expensive.

The framework also takes a number of inputs that characterize the operating environment of the floating wind turbine. These inputs are: water depth, a set of wave spectra, and a set of corresponding steady wind speeds. The objective function values can be aggregated across the set of environmental conditions using a weighted averaging scheme appropriate to the relative importance of each condition. These inputs reflect the nature of the framework as a global optimizer. Once an operating environment and common design constraints are provided, the framework will explore all the options within those inputs according to its abilities.

MODELLING AND EVALUATION METHODOLOGY

The evaluation of each point in the design space and calculation of its objective function value are handled by a six-DOF frequency-domain model created in Matlab. This linear model provides a computationally-efficient way of coupling the dynamics of the wind turbine, mooring system, and floating platform. Loads from steady winds and regular (monochromatic) waves are included. The DOFs considered are the six rigid-body modes of the platform. By definition, the frequency-domain model assumes that the platform motions are at the same frequency as the incident waves and that the incident waves are regular. While this means that the transient response of the system cannot be modelled, the assumption of linearity implies that the responses at different wave frequencies can be superimposed according to a wave spectrum to predict the system behaviour in irregular sea states, as was done in Eq. (2).

Equation (4) shows the generic equation of motion of a floating body for a unit-amplitude wave, where M is system mass, A is hydrodynamic added mass, B is system damping, C is system stiffness, X is the wave excitation vector, ξ is the vector of system displacements, and ω is wave frequency. Applying the assumption that the waves and body motion are sinusoidal and of the same frequency, Eq. (4) can be rewritten as shown in Eq. (5).

$$[M + A(\omega)]\ddot{\xi} + B(\omega)\dot{\xi} + C\xi = X(\omega) \tag{4}$$

$$\left\{-\omega^2\left[M + A(\omega)\right] + i\omega B(\omega) + C\right\}\xi(\omega) = X(\omega) \tag{5}$$

The complex response of the platform, ξ, can then be solved for at any frequency if the coefficient matrices ($M, A, B, C,$ and X) are known. From the resulting response amplitude operators, the objective function can be evaluated.

Platform Linear Hydrodynamics

For the floating platform dynamics, the theory of linear hydrodynamics is used, which simplifies calculation of the wave diffraction and wave radiation forces on the platform by analyzing them independently. The theory is based on Airy wave theory, which assumes mild (non-steep) waves and models the hydrodynamics using potential flow theory, thereby neglecting viscous effects. Furthermore, it assumes that the movements of the body are small relative to the body size. Because the problem is approximated as linear, superposition can be used to break the hydrodynamic forces on the body down into three independent components: hydrostatics (buoyancy), diffraction (wave excitation) and radiation (added mass and wave-radiation damping) (Jonkman, 2007). Hydrostatic effects are represented by the stiffness matrix $C_{i,j}$, which describes the magnitude of the reaction force/moment in each DOF i for platform displacement/rotation in each DOF j. Diffraction effects are represented by a vector of wave excitation coefficients, $X_i(\omega)$, which relate the wave-induced force/moment in each DOF of the platform. These coefficients are complex, in order to specify the phase relationship between incident waves and resulting loadings, and frequency dependent. Radiation effects are represented by a damping matrix, $B_{i,j}(\omega)$, and an added mass matrix, $A_{i,j}(\omega)$. The frequency-dependent coefficients in these matrices represent the components of the forces/moments caused by platform velocities and platform accelerations, respectively (Kim, 1999).

The linear hydrodynamic coefficients discussed above are generated for each platform design by WAMIT, an industry-standard linear hydrodynamics solver. A Matlab interface was made to a meshing routine created in C++ to automatically panelize the platform surface and generate the WAMIT geometry file. This interface also connects to a script that performs the platform mass calculations and handles the calls to the mooring line model. The interface returns a variety of aggregate platform properties to the Matlab-based frequency-domain model of the combined system. The hydrodynamic impacts of the connective elements between multiple cylinders are neglected at this time, as unlike their inertial effects, the elements' hydrodynamic effects are extremely sensitive to their exact configuration, which is difficult to predict. This is an area for future improvement.

Viscous Hydrodynamic Damping

Heave plates, with their unstreamlined shape and sharp edges, are designed to produce large amounts of added mass and viscous drag. Their viscous drag, which is quadratic in nature, is not modelled by WAMIT's linear potential flow method so another model is required to capture it. A common approach is based on the drag term of Morison's equation where the viscous drag force, *F*, is modelled as the product of a drag coefficient, heave plate area, and the square of the relative fluid velocity *u(t)*. To fit into a frequency-domain model, a linearized representation is required:

$$F(t) = \frac{2}{3}\rho_w D^3 \omega B' u(t) \tag{6}$$

where *D* is the heave plate diameter and *B′* is a function of the Keulegan-Carpenter number for which empirical relations have been developed (Tao and Dray, 2008).

The approach of Eq. (6) was implemented into the combined frequency-domain system model. Wave kinematics are not included in the calculation of relative fluid velocity for simplicity, on the grounds that heave plates are at a depth where wave velocities are quite low. Because the linearization depends on the amplitude of motion, it is a co-dependent function with the solution of the equation of motion for the system. Therefore, an iterative approach is taken in solving for the motions of the platform, with the heave plate viscous drag linearization updated at each iteration. This model provides the viscous drag contribution to the platform damping in the three DOFs most affected by the heave plates - heave, pitch, and roll. Viscous drag contributions in other DOFs are ignored. The wave-radiation damping and added mass from the heave plates are provided by the WAMIT analysis.

Wind Turbine Dynamics

The effects of the wind turbine can be added to the frequency domain model if they are linearized. The wind turbine used is the NREL offshore 5 MW baseline turbine, a hypothetical design with realistic specifications designed as a benchmark model for use in the design and modelling of offshore wind turbine support platforms (Jonkman et al., 2009). Following the linearized approach, the wind turbine mass, damping, and stiffness coefficients are frequency-independent values that simply add to the support platform coefficients in the equation of motion of the overall system. These linearized coefficients were obtained using FAST's linearization functionality for each wind speed condition. Limiting the complexity of the model necessitates that these linearizations be generated at a fixed static pitch angle rather than one that is adjusted for each platform at the thrust load of each wind speed. A value of zero pitch was chosen because many platforms pitch very little or use techniques such as active ballast to eliminate significant static pitch angles.

Mooring Lines

The generation of mooring line stiffness matrices is handled by a custom routine that calls a quasi-static mooring line model. The mooring model in this case is Catenary, the mooring line subroutine of FAST, which was translated into C++ to provide easy integration with other parts of the framework that are also implemented in that language. The linearization routine accepts the decision variables, water depth, and wind speeds, applies the mooring configuration algorithm discussed previously to determine the mooring configuration, and uses several layers of iterations and perturbations when calling the quasi-static mooring line model to obtain linearized mooring stiffness matrices. A separate matrix is generated for the displaced equilibrium position of the platform corresponding to the wind turbine thrust load at each wind speed being analyzed. As noted by Tracy (2007), the effect of the mooring system changes as the thrust force from the wind causes the platform to be displaced from its centered position, therefore it is important to linearize the mooring system reactions about these displaced equilibrium positions.

The final equation of motion of the system, including all of the factors used in the analysis, is:

$$\left\{ \begin{aligned} & -\omega^2 \left[M_{turbine} + M_{platform} + A(\omega) \right] + i\omega \left[B_{turbine} + B_{rad.}(\omega) + B_{visc.}(\omega,\zeta) \right] \\ & + C_{mass} + C_{hydrostatic} + C_{turbine} + C_{mooring} \end{aligned} \right\} \zeta(\omega) = X(\omega) \tag{7}$$

RESULTS

The operation of the optimization framework can be most easily demonstrated for simplified design spaces where only three decision variables are active at a time. Three-dimensional scatter plots of the individuals evaluated by the GA can illustrate the algorithm's convergence about local optima and characteristics of the design space (including regions that are promising, regions that are poor, and infeasible regions). The results that follow were generated using an equally-weighted set of two environmental conditions: 8 m/s winds with a sea state of 2 m significant wave height and 5 s peak period, and 12 m/s winds with a sea state of 3 m significant wave height and 7 s peak period. The water depth is set at 320 m. It should be kept in mind that the results are specific to these environmental inputs.

The scatter plot of Figure 3 shows the framework's exploration of a design space for a single-cylinder platform. The three variables of this design space are draft, radius, and top taper ratio. No additional cylinders are permitted, and the mooring system is set to the widest-spaced catenary configuration (x_M=2). The colour of each data point represents that design's scaled fitness value as used by the GA. A value of zero indicates a least-fit individual and a value of one indicates a locally-optimal individual. The points evaluated by the GA can be seen to cluster around the two clear local optima in the design space, one corresponding to a spar-buoy configuration and the other corresponding to a large barge-style configuration. Figure 4 shows the panelized wetted area of the optimal design in the spar-buoy cluster, and Fig. 5 shows the same for the optimal design in the barge-style cluster. The darker grey panels indicate the level of ballast within the platform. Figure 6 provides a wider view of the spar-buoy design to illustrate the configuration of the mooring lines. The spar buoy design has a draft of almost 150 m, significantly more than the Hywind's 120 m draft; this is because the GA will seek the largest structure that satisfies the constraints to minimize the motion-based objective function. The other design is a deep barge with a taper at the top. Though not an intuitively-optimal design, this configuration shows how when a barge is given all the mass available to a spar buoy design, it can improve its stability best by increasing is draft and adding ballast. However, the nacelle accelerations for this design are double those of the spar-buoy.

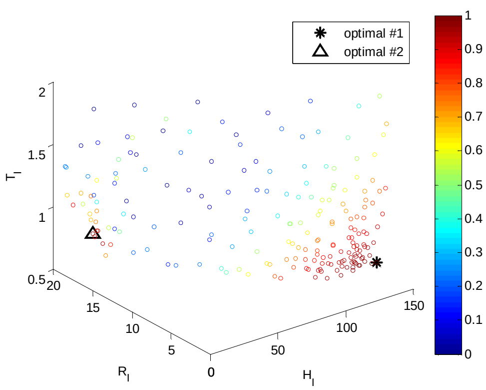

Fig. 3. Single cylinder design space exploration.

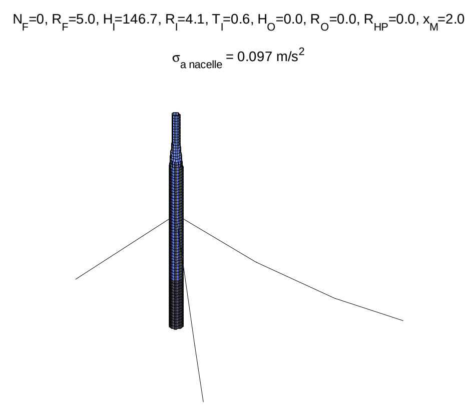

Fig. 4. Single cylinder optimal design #1.

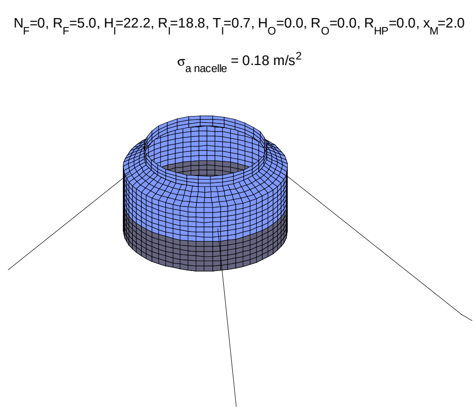

Fig. 5. Single cylinder optimal design #2.

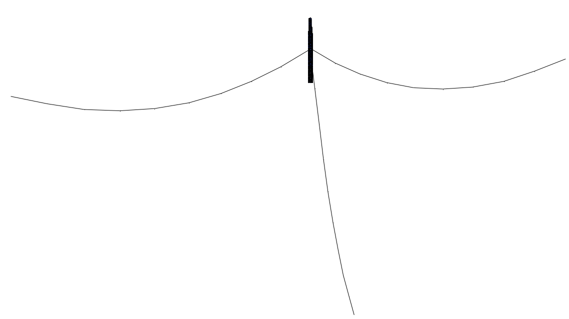

Fig. 6. Mooring system of design #1.

Figure 7 shows the exploration of a design space for a tri-floater configuration with varying draft, cylinder radius, and cylinder spacing. Heave plates are excluded and the widest-spaced catenary mooring configuration is again used for this case. The effect of the framework's constraints can be clearly seen in the limited extent of the cloud of points. Similarly to the previous design space, two local optima can be identified. The first optimal design (Fig. 8) features a spacing of 36.7 m, a draft of 21.6 m, and a radius of 4.2 m. The trend is clearly toward larger cylinder spacings and smaller cylinder radii, presumably in order to increase water plane inertia. The second local optimum, which is much weaker compared to the first, is a design (Fig. 9) with a slightly smaller cylinder radius but double the cylinder draft, the inclusion of ballast, and closer cylinder spacing. In this design, the stability of wider cylinder spacing has been traded off for the stability provided by a deeper draft and the use of ballast, while still respecting the structural expense constraint on the platform.

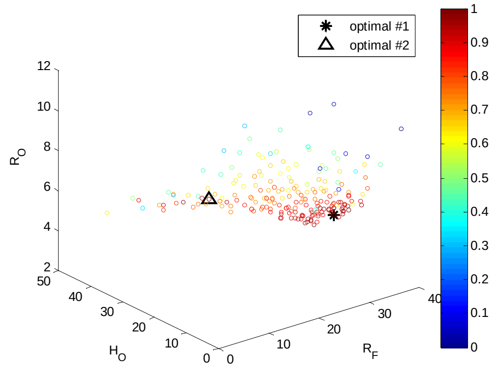

Fig. 7. Three cylinder design space exploration.

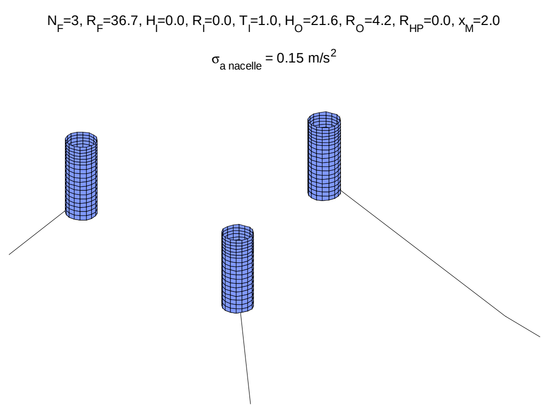

Fig. 8. Three-cylinder optimal design #1.

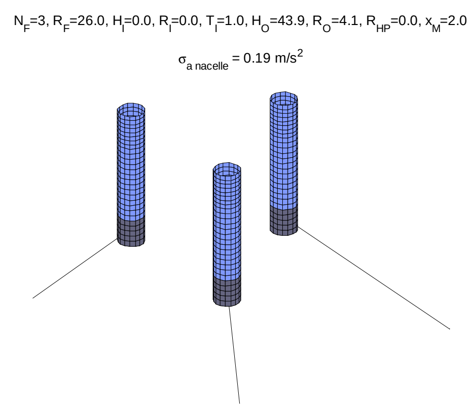

Fig. 9. Three-cylinder optimal design #2.

Figure 10 shows the exploration of a design space for a tri-floater with cylinders of fixed size but varying spacing, heave plate size, and mooring configuration. This arrangement is a way to explore the trade-offs between three different means of making a tri-floater more stable – float spacing, heave plate area, and mooring line tension.

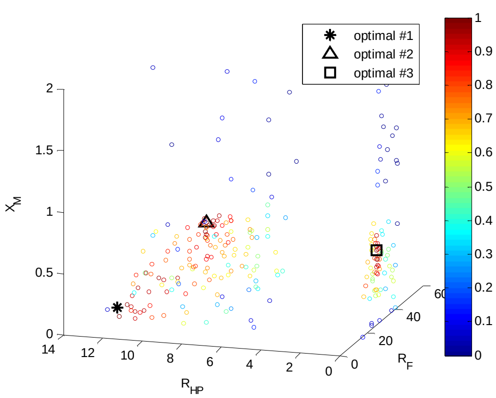

Fig. 10. Tri-floater design space exploration.

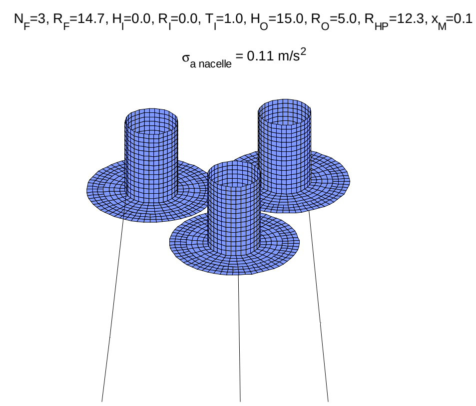

Fig. 11. Tri-floater optimal design #1.

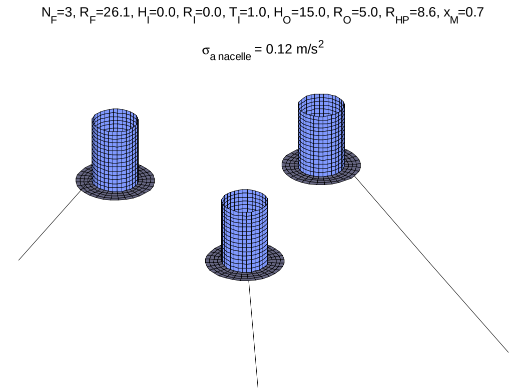

Fig. 12. Tri-floater optimal design #2.

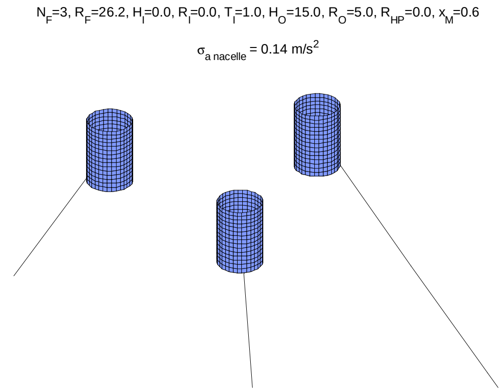

Fig. 13. Tri-floater optimal design #3.

Here, three distinct local optima can be seen – each with values of x_M less than 1, indicating taut mooring configurations. The first optimal design (Fig. 11) features closely-spaced cylinders and very large heave plates. The second locally-optimal design (Fig. 12) features a much greater cylinder spacing but smaller heave plates (the structural mass of the latter traded off for the former). It is interesting to note that this cylinder spacing is within 0.5 m of that of the WindFloat design. The third locally-optimal design (Fig. 13) features similar cylinder spacing but no heave plates (the structural mass of the heave plates traded off this time for increased tension in the mooring system). The absence of local optima in the slack-moored portion of the design space is also notable, and suggests that the expense associated with taut mooring systems may be under-represented in the current structural expense constraint.

A design space of six dimensions was constructed to explore the options between different numbers of cylinders and different cylinder dimensions. The six decision variables used in this case are inner cylinder draft, inner cylinder radius, number of outer cylinders, spacing of outer cylinders, outer cylinder draft, and outer cylinder radius. Setting R_I=0 or R_O=0 disables the inner or outer cylinders. A slack mooring configuration was used in this case, and heave plates on the outer cylinders and taper on the inner cylinder were disabled for simplicity. With the larger design space, a number of local optima were identified by the algorithm; four of them are illustrated here for brevity. Figure 14 shows the most optimal design, five moderately-spaced cylinders with a smaller central sixth cylinder. The second local optimum (Fig. 15) again has 5 outer cylinders and one inner cylinder but with more of the volume provided by the inner cylinder and greater outer cylinder spacing. The third local optimum is similar to the first and second. The fourth local optimum (Fig. 16) continues the trend toward smaller widely-spaced outer cylinders around a larger central cylinder, this time with four outer cylinders, a deeper central cylinder, and, unlike the other designs, no ballast. The fifth local optimum (Fig. 17) consists of three widely-spaced outer cylinders and a wide central cylinder. A preference for a combination of outer cylinders and an inner cylinder is noticeable in these optima, with trends of progressively shifting the balance of displacement from the outer cylinders to the inner cylinder, reducing the number of cylinders, and increasing the cylinder spacing from center in successively less-optimal designs. The lack of a spar-buoy in these results is surprising, until one realizes that disabling the possibility of taper on the central cylinder is a significant detriment to the spar buoy; the wave excitation forces are significantly increased to the point that it is no longer competitive. Keeping in mind this exclusion, the exploration of the design space here points to an interesting combination of inner and outer cylinders – a rarity in current floating wind turbine designs, but a configuration that previous research also pointed toward (Hall et al., 2012).

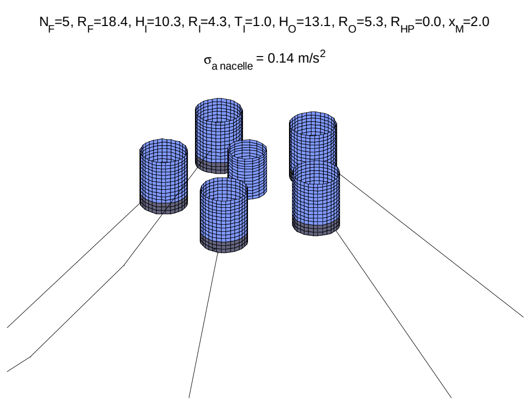

Fig. 14. Multi-cylinder optimal design #1.

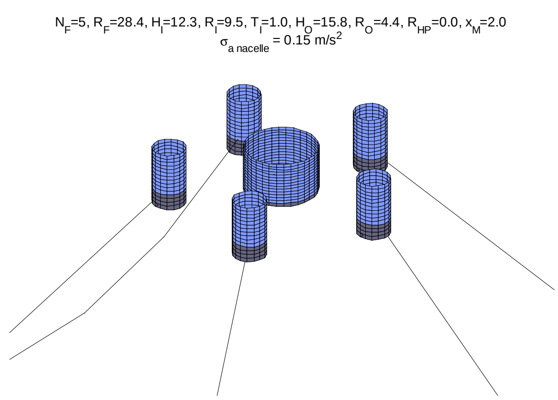

Fig. 15. Multi-cylinder optimal design #2.

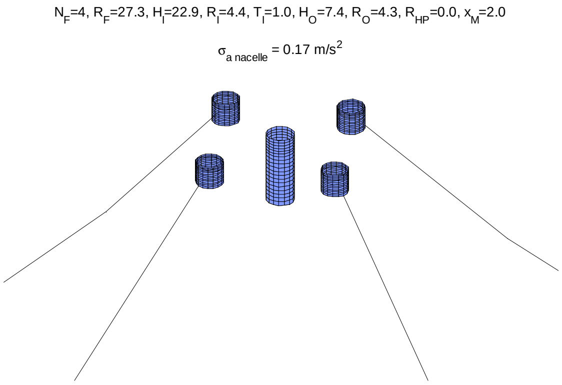

Fig. 16. Multi-cylinder optimal design #4.

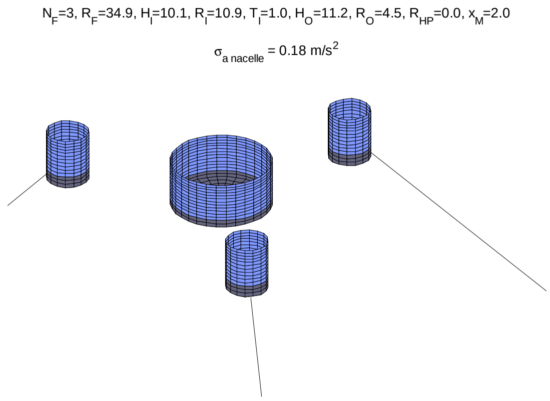

Fig. 17. Multi-cylinder optimal design #5.

When the full design space described by the support structure parameterization is explored, the algorithm identifies many local optima. The first optimal design (Fig. 18) bears similarities to the spar-buoy design found in the single cylinder design space (Fig. 4), however it features taut mooring lines and is unballasted. The second locally-optimal design (Fig. 19) is a three-cylinder arrangement with heave plates similar to standard tri-floater configurations such as the WindFloat design, but with a sizeable central cylinder as well. The third locally-optimal design (Fig. 20) is highly unusual in its large number of small outer cylinders with heave plates, tensioned mooring lines, and a large central cylinder that is both wide at the water plane and deep. The fourth locally-optimal design (Fig. 21) is similar to the design of Fig. 19 but with five outer cylinders and a deeper inner cylinder. The variety in these results demonstrates the framework's effectiveness at identifying diverse locally-optimal support structure configurations.

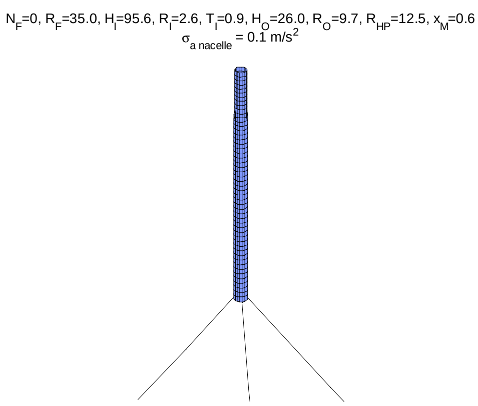

Fig. 18. Full design space optimal design #1.

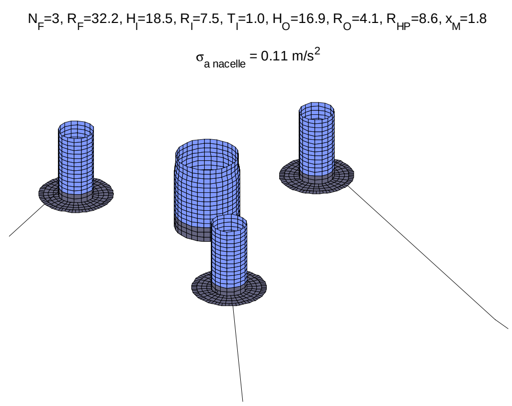

Fig. 19. Full design space optimal design #2.

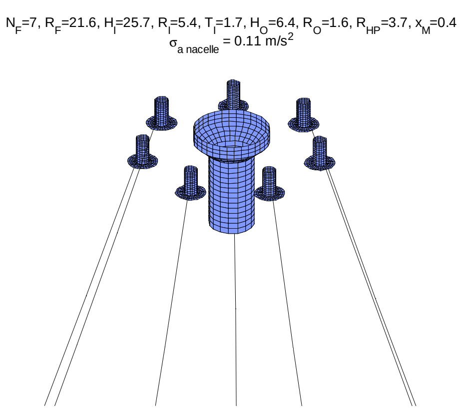

Fig. 20. Full design space optimal design #3.

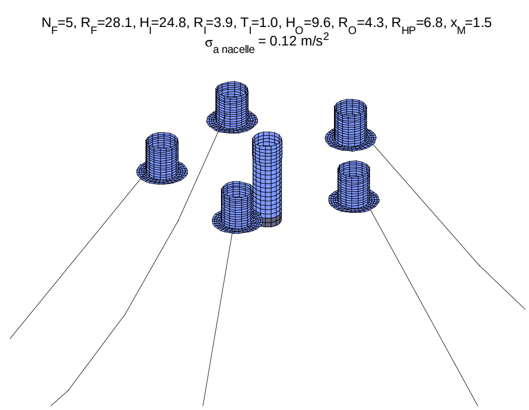

Fig. 21. Full design space optimal design #4.

CONCLUSIONS

A global optimization framework has been developed for the floating wind turbine support structure design problem. A genetic algorithm handles the optimization over the often-discontinuous design space. A platform geometry scheme based on arrays of vertical cylinders and a mooring configuration scheme with one dedicated decision variable provide a flexible and efficient means of describing a wide range of support structure configurations. A platform ballast and mass model and a set of constraints relating the platform and mooring system complete the description of the support structure properties as a function of the decision variables. An analysis capability was assembled to evaluate the support structure performance in terms of platform motions in six degrees of freedom. The panel method code WAMIT, supplemented by a custom viscous drag model, provides platform hydrodynamic characteristics, while a quasi-static mooring model provides linearized mooring system stiffnesses and the floating wind turbine code FAST provides linearized wind turbine effects. A frequency-domain model couples these inputs together and evaluates the system dynamics which in turn inform the objective function. In this case, the objective chosen is the minimization of nacelle accelerations. Constraints are implemented to cap the total expense of the support structure, providing a level-cost playing field to see which configurations can provide the greatest stability.

Results of design space explorations using limited numbers of decision variables show optimal configurations that in many cases bear strong similarities to current concepts such as the Hywind and WindFloat designs. Other optimal configurations are found to be more unique, such as those that combine a central cylinder with a number of outer cylinders. Results using the full design space described by the parameterization include a diverse set of locally-optimal configurations, some that are quite similar to current designs and some that fall outside currently-studied concepts.

These results demonstrate the value of the present framework in verifying the optimality of existing designs and illuminating previously-unexplored optimal designs to a degree not previously possible. The framework's exploration of the design space is also valuable in itself in how it shows the nature of the design space - including the bounds imposed by expense, buoyancy, or stability constraints; the general effects of different parameters on the support structure's performance; and the presence of multiple local optima. For fewer dimensions, the GA approach is akin to an intelligent, selective parameter study approach and allows insights to be drawn from parametric analysis. For greater dimensions, where parametric insights are less accessible, the GA serves its greater value as an optimization tool that can be trusted to intelligently explore the vast design space.

FUTURE WORK

While the framework has successfully demonstrated its effectiveness for exploring the design space, adjustments and improvements are planned in a number of areas. One such area is the prediction of properties of the connective structural members between cylinders. A very simple model to estimate the distributed mass of these members was implemented. Expansion and verification of this model is needed, as is a scheme to include the presence of these elements in the hydrodynamic analysis.

Another area for improvement concerns the mooring lines. The greater-than-expected preference for taut mooring line configurations in the results suggests that the current structural expense constraint may under-represent the expense of different mooring configurations. As well, the material properties and diameter of the mooring lines are currently fixed; these should be made to adapt based on the expected mooring line tensions. A further capability that should be added is the use of horizontal spokes radiating from the bottom of the central cylinder in the case of taut vertical mooring line configurations to give the mooring lines a greater moment arm on the platform.

The platform geometry parameterization could also use further attention. While the range of possibilities provided by the current eight-parameter scheme is quite large, there is room for improvement in terms of additional factors that should be parameterized to further widen the design space or more intelligent and efficient ways of describing the range of possible geometries.

Lastly, the optimization problem itself could be adjusted. The current optimization problem is set up to constrain the overall expense of the structure and then find the most stable configurations within that constraint. This is valuable in exploring the design space and discovering which configurations are most stable, but it does not necessarily lead to optimal designs from a cost standpoint. A reframing of the optimization problem to apply only performance-related constraints and include a reasonably-accurate cost model for the objective function could provide results geared more toward developing the most cost-effective support structure designs.

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