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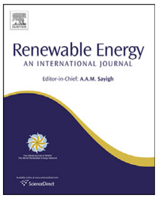

Hydrodynamics-based floating wind turbine support platform optimization: A basis function approach

Matthew Hall*, Brad Buckham, Curran Crawford

University of Victoria, British Columbia, Canada

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ABSTRACT

The floating wind turbine support structure design problem is complicated by conflicting technical objectives and innumerable platform geometry options. Previous support structure optimization studies have been limited in their ability to evaluate the full design space due to their adherence to certain assumptions about the physical platform configuration. The present work is an effort toward developing an alternative form of the support platform optimization problem – one that abstracts details of the platform geometry and deals instead with hydrodynamic performance coefficients – in order to provide a more complete and intuitive exploration of the design space. A basis function approach, which represents the design space by linearly combining the hydrodynamic performance coefficients of a diverse set of basis platform geometries, was taken as the most straightforward way of physically constraining the platform hydrodynamic performance. Candidate designs are evaluated in the frequency domain using linearized coefficients for the wind turbine, platform, and mooring system dynamics. The platform hydrodynamic coefficients are calculated according to linear hydrodynamic theory. The optimization objective is to minimize the nacelle acceleration under several operating conditions. Optimization results for a slack catenary mooring system indicate the benefits of combining submerged volume with a widely dispersed water plane area. Results for a tension leg mooring system are consistent with conventional TLP designs. The intent is to use these results as starting points for more traditional platform parameter optimization. Examination of the possible physical interpretations of linearly combining basis platform coefficients reveals that certain aspects of this approach may have poor physicality. This points to the need to expand this first attempt with more sophisticated ways of representing the constrained hydrodynamic performance variables.

1. Introduction

The goal of this study was to develop a “hydrodynamics-based” approach to exploring the floating wind turbine support structure design space. Such an approach operates on the hydrodynamic characteristics rather than the underlying geometry of candidate designs, bypassing the computationally-demanding process of calculating hydrodynamic coefficients for every design. It was hoped that this approach could simplify and clarify the otherwise complex and obfuscated support structure design problem, and lead to the identification of key platform hydrodynamic characteristics that maximize performance. Designing a floating platform and mooring system to stably and economically support a wind turbine is no easy feat, thanks to competing technical objectives, numerous design options, and the complexity of the coupled aero-hydro-elastic dynamics involved.

1.1. The design problem

When a wind turbine is situated on a floating platform, it is exposed to a new range of motions. These motions, excited by both wave forces on the platform and wind forces on the turbine, make for a complex coupled aero-hydro-elastic dynamics problem. The two degrees of freedom (DOFs) introduced by the floating platform that are usually most problematic to a wind turbine are surge and pitch – fore-aft translation and fore-aft tilting of the platform, respectively. These DOFs are easily excited by wave loadings and, to a lesser degree, fluctuating wind thrust loadings, and they contribute to bending moments in the tower and the blades – two of the most critical structural loads.

Rather than expend resources creating stronger turbines to handle the loads from these new motions, designers have focussed on designing the support structure to minimize the motions. This is most easily done by making the structure hydrodynamically transparent – with a *small* water plane area and moment of inertia – in order to minimize loadings from waves. At the same time,

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* Corresponding author.
E-mail address: mtjhall@alumni.uvic.ca (M. Hall).

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however, the steady overturning moment from the wind turbine thrust load must be resisted. In a floating structure, the easiest way to do this is by using a *large* water plane moment of inertia, which exacerbates hydrodynamic loads from waves. Alternative ways of providing the required static stiffness in pitch are by the use of ballast or taut mooring lines.

The three strategies for providing static stability to the platform constitute the three stability classes for floating support structures.

Buoyancy-stabilized designs rely on a large water plane area moment of inertia to raise the platform's metacenter above its center of gravity. Referred to as semisubmersibles, these platforms are often in the shape of a barge or an array of three or more vertical cylinders connected with a truss structure. The shallow drafts of buoyancy-stabilized platforms make for simple installation and flexible siting. The lack of ballast reduces size and material requirements. The trade-off is that the large water plane area can make the platform susceptible to severe wave-induced motions. Heave plates are often added to reduce wave-induced motions.

Ballast-stabilized designs use a deep draft and heavy ballast to locate the platform's center of gravity well below its center of buoyancy. These designs use a spar-buoy configuration – a long slender vertical cylinder. With a minimal water plane area, spar-buoys are resistant to wave induced motions, but the amount of ballast adds size to the design, raising costs, and the large draft limits siting and installation options.

Mooring-stabilized platforms, often called tension leg platforms (TLPs), make use of taut often-vertical mooring lines to hold the platform below its neutral buoyancy depth, providing a pretension of sorts to effectively counter any heaving or pitching motions. With a minimal water plane area and taut mooring lines, the TLP configuration is extremely resistant to pitching motions. Its disadvantages involve costs and siting limitations associated with the high tension mooring system, and additional buoyancy needed to counter the mooring line tension.

1.2. Conventional geometry-based design space exploration

There is still no consensus as to which stability class or platform configuration holds the most promise. Studies have been done in the past both comparing and optimizing floating platform designs. Comparison efforts of specific designs can afford to use computationally-intensive time-domain simulation tools to provide a detailed and reliable comparison of leading designs from each of the three stability classes. See for example the work of Jonkman and Matha [1] and Robertson and Jonkman [2]. While these studies are an excellent later-stage tool for identifying the best design, they lack the ability to explore the design space for new design concepts. Optimization efforts and parameter studies, which are capable of design space exploration, tend to rely on lower-fidelity computationally-efficient frequency-domain modeling techniques.

The conventional method of finding an optimal floating platform shape is by parametric optimization, in which the geometry of the platform is represented by a number of parameters that become decision variables. Parametric approaches are attractive because they reduce the design variables to a manageable number so that it is possible to analyze and draw conclusions about design alternatives. While this works well for determining the optimal dimensions of a single design concept, it is difficult to create a parameterization that can describe different configurations (e.g. both a spar-buoy design and a three-column semisubmersible). Consequently, parameterizing such a complex design problem tends to artificially constrain the design space and limit design creativity.

The best example in the literature of a parameter study that considers a broad range of platform configurations is the one done by Tracy at MIT [3]. The parameterization uses a cylindrical platform of variable dimensions and mooring lines of variable tension and angle – thereby spanning each stability class, from TLPs to spar-buoys to cylindrical barges – and frequency-domain modeling to find Pareto-optimal support platform configurations. Unfortunately, this parameterization is still limited to single-cylinder configurations; multi-cylinder configurations – an important part of the design space given the recent trends toward semisubmersible platforms – are excluded.

1.3. Hydrodynamics-based optimization

The idea of "hydrodynamics-based" optimization is to represent the design space in terms of hydrodynamic performance characteristics rather than geometric characteristics. The motivation behind this idea is to represent the design space in a way that is more intuitively related to the performance characteristics that a designer needs to be mindful of. By avoiding the assumptions of a geometric parameterization, a hydrodynamics-based approach may be able to explore the design space more widely. By avoiding in-the-loop calculation of hydrodynamic properties from platform geometry (using e.g. WAMIT), a hydrodynamics-based approach will be significantly faster than conventional optimization approaches. The strategy is to look for optimal support platform performance characteristics without making *a priori* assumptions about the platform geometry that would limit the design space. In order to achieve this, the geometric decision variables that describe the geometry of the platform need to be replaced with hydrodynamic performance-related decision variables that describe the hydrodynamic characteristics of the platform (such as hydrostatic stiffnesses and wave excitation coefficients). The challenge is to apply constraints to these characteristics so that they are realistic, without simultaneously making assumptions that over-constrain the geometry of the platform. If this can be achieved, then we will have a powerful new way of exploring the design space – a process that will yield optimal sets of platform performance characteristics that can then be used as performance targets for more detailed support platform design work.

The most direct approach toward "hydrodynamics-based" optimization would be to treat each of the hydrodynamic parameters of the platform – added mass, damping, stiffness, and wave-excitation – as decision variables. The first problem with this is that these are all matrices or vectors, and most of them are frequency dependent, rendering the problem domain impossibly large. The second problem is that without imposing constraints on, and between, these variables, the majority of the design space would be completely unphysical and not representative of the real design problem. But to follow the conventional approach of generating hydrodynamic coefficients from specific platform geometries would mean losing the generality and insight that the current work aims to achieve. The task, then, is to find a middle ground – to identify a small number of generic platform properties that can be used as decision variables, that are sufficiently detailed to provide estimation of hydrodynamic coefficients, and that are still general enough to represent the full floating platform design space.

2. Basis function optimization approach

A "basis function" approach is one possibility for hydrodynamics-based optimization that offers a simple means of representing the physical constraints. The idea is to use a collection of unique geometrically-defined platform designs as "basis designs" whose hydrodynamic performance coefficients can be linearly combined to approximate the characteristics of any platform in the design space. This approach is analogous to basis functions defining a function space or basis vectors defining a vector space.