On the Controllability of a Floating Offshore Wind Turbine

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Abstract. An analytical method for assessing the controllability of floating offshore wind turbines (FOWTs) is presented in this work. Modern linear control theory principles are applied to linearized FOWT models to establish quantifiable metrics to determine advantageous, or disadvantageous, differences in turbine models from a controls perspective. One use of such a metric is to consider the amount of work necessary to move a floating turbine back to an equilibrium point. We use a simplified point-mass model to demonstrate this idea. The idea is then translated to the DTU 10MW wind turbine on floating semi-submersible platforms. This work concludes with a discussion of the many potential uses for the quantifiable values associated with controllability within the wind turbine research space.

1. Introduction
Growing wind energy penetration in the global energy market is driving the development of floating offshore wind turbines (FOWTs). Increased wind resource availability and consistency, proximity to major population centers, and relative ease of manufacturing and deployment are just a few of the advantages of offshore wind turbines. The use of a floating foundation offers access to offshore wind resources in areas with water depths greater than 50 meters. Nearly all of the available wind energy resources on the west coast of the United States are areas of deep water. The presented work introduces an analytical method to assess the controllability of a FOWT to better inform control systems and structural design development. Specifically, we aim to assign quantifiable metrics to a controllability analysis such that differences in turbine models can be identified within a control systems framework.

Iterative optimization of FOWT designs is not a new concept. An optimization tool for floating substructures was presented in [1], though no specific control system is considered. An optimization of a FOWT spar platform is presented in [2]. The analysis in [3] considers the control system in a multi-fidelity simulation tool, where blade pitch controllers are specifically designed for the three different FOWT platform models considered. The study in [4] presents some of the first work that includes a fully integrated turbine controller in the design optimization, where a Linear Quadratic Regulator (LQR) is defined for various platform models, with the goal of optimizing a FOWT platform hull shape to minimize wind and wave excitation forces.

We introduce a controllability analysis method to theoretically quantify the capabilities of a FOWT control system. This builds on an idea briefly mentioned by Lemmer [5], where he discusses the idea of considering the minimum energy control as an indicator of optimal design behavior. The mathematical foundation for this is the Controllability Gramian [6]. Amongst many other things, analysis of the Controllability Gramian offers insight into the ability to control the system state towards different “directions” and the amount of “control energy” to do so. In order to offer a simple explanation of
some of these methods, we present a point-mass example. This is then expanded to show the same ideas within the context of FOWTs. Finally, we present a discussion of potential uses for metrics such as these and what they might offer to the wind energy research community, specifically for the purpose of wind turbine optimization with a consideration of the control system.

2. Theory

Linearized models of a floating wind turbine are used to analyze the controllability of the system. In this work, the linearized models are found using OpenFAST [7] at specified, above-rated operating points. Through investigation of the Controllability Gramian (1), we can gain some insight into the controllability of the system [6].

A linear system can be defined by

\[ \dot{x}(t) = Ax(t) + Bu(t), \]

where \( x \) is a state vector, \( A \) is a system matrix, \( u \) is a vector of system inputs, and \( B \) is an input gain matrix. For any linear time-invariant system, the finite-time Controllability Gramian is defined as

\[ W_c(t) = \int_{t_0}^{t_1} e^{A(\tau-t_0)}BB^T e^{A^T(\tau-t_0)}d\tau. \]  

(1)

If \( W_c \) is non-singular, we consider the system to be controllable, meaning that there exists an input which can move the initial state of the system \( x_0 \) to a final state \( x_{des} \) within the finite amount of time \( t_1 - t_0 \) [6]. For the remainder of this formulation, we assume \( t_0 = 0 \) for simplicity.

2.1. Energy methods

A convenient way to quantify the controllability of the system is to consider the amount of “control energy” it takes to move the system to a desired state \( x_{des} \). An intuitive example of the idea of control energy, that will be explored more, is to analyze the energy necessary to move a mass to a desired location within a fixed amount of time. Somewhat less intuitively, but related to wind energy systems, one could analyze the amount of blade pitch actuation necessary to move a floating wind turbine’s tower-top some amount, within a finite amount of time. The minimum energy control input \( u_{min} \) to move a system to some desired state \( x_{des} \) from \( x_0 \) within a finite-time \( t_1 \) is [6]

\[ u_{min}(t_1) = -B^T e^{A^T(t_1)}W_c^{-1}(t_1)[e^{At_1}x_0 - x_{des}]. \]  

(2)

The total amount of control energy to move from \( x_0 \) to \( x_{des} \) is

\[ E_{x_{des}}(t_1) = \int_0^{t_1} u^T(\tau)u(\tau)d\tau. \]  

(3)

Substituting (2) into (3) results in a minimum energy control solution, where

\[ E_{x_{des, min}}(t_1) = [e^{At_1}x_0 - x_{des}]^T W_c^{-1}(t_1)[e^{At_1}x_0 - x_{des}]. \]  

(4)

Notably, (3) suggests that the the idea of “control energy” does not necessarily relate to units of actual energy (i.e., Joules). If the system’s input is a force [N], then the minimum control energy \( E_{x_{des}} \) has the units \([N^2s]\). We use this formulation to perform a simple investigation into the amount of energy it takes to move a system back to its “home” state \( x_{des} \) from an initial state \( x_0 \). This work presents a simple example to further clarify the motivation behind this type of analysis, and then applies the analysis to a floating wind system. One could, in theory, define \( x_{des} \) to be any state within the system’s domain and an analysis of the amount of control energy to move to this state could be performed in the same way.
2.2. Controllable directions

We introduce the idea of controllable directions to offer some additional linear systems methods that may be applicable to the floating offshore wind turbine optimization problem. The singular value decomposition (SVD) is the theoretical base for our analysis of the controllable directions of the system, where the infinite-time Controllability Gramian can be expressed as the product of three matrices,

\[ W_c(t = \infty) = U \Sigma V^T. \]  

By the definition of the SVD, \( U \) and \( V \) are real or complex unitary matrices, and \( \Sigma \) is a square, diagonal matrix with non-negative real numbers \( \sigma_i \in \{\sigma_1, \ldots, \sigma_n\} \), where \( n \) is the rank of the matrix \( W_c \). The Controllability Gramian is a symmetric positive-semidefinite matrix by definition, so the matrices \( U \) and \( V \) are square matrices and \( U = V \). Figure 1 shows the singular values for the simplified DTU 10MW wind turbine [8] on the NAUTILUS-10 floating substructure [9] used in this study. The singular values \( \sigma_i \) are ordered from largest to smallest, and Figure 1 shows that \( \{\sigma_1\} \gg \{\sigma_2, \ldots, \sigma_{11}\} \). The linearization was conducted for a wind turbine system with first-order platform and generator dynamics with unstable or uncontrollable states. The system was linearized about inflow wind conditions of 14 m/s and still water.

We define \( V \) to be the vectors \( \{v_1, \ldots, v_n\} \) such that

\[ V = \begin{bmatrix} \vdots & \vdots & \vdots \\
 v_1 & v_2 & \ldots \\
 \vdots & \vdots & \vdots 
\end{bmatrix}. \]  

(6)

Note that, because \( \sigma_1 \gg \{\sigma_2, \ldots, \sigma_{11}\} \), \( v_1 \) is the primary “direction” in \( V \) and is in the functional range space of \( \Sigma \). We denote this space as the functional range space because \( \sigma_1 \gg \{\sigma_2, \ldots, \sigma_{11}\} \), and \( \{\sigma_2, \ldots, \sigma_{11}\} \approx 0 \). An analysis of \( v_1 \), shows which direction in the state space is the most controllable.

3. A simple example

In order to better articulate the idea of control energy, we employ a simple point-mass example as shown in Figure 2. The mass can be moved by two forces, \( F_1 \) and \( F_2 \). The force \( F_1 \) always acts along the x-axis. The force \( F_2 \) is able to be rotated by an angle \( \theta \) from the vertical, where \( \theta \) is an input to the system. The system is such that when \( \theta = 0^\circ \), \( F_1 \) and \( F_2 \) are orthogonal, and when \( \theta = 90^\circ \), \( F_1 \) and \( F_2 \) are both aligned with the x-axis. The result is a fourth-order system, where the state is defined as

\[ \bar{x} = [x \ x \ y \ y]^T. \]  

(7)
Figure 2. A point-mass, \( m \), on a surface at the origin. The mass is attached to the walls by two linear springs defined by the same spring constant \( k \), and the mass is on a rough surface with damping constant \( c \). The springs always act in the horizontal (\( x \)) and vertical (\( y \)) directions.

In this simple example, we define \( m = 10 \) kg, \( k = 5 \) N/m, and \( c = 2 \) kg/s, where \( k \) and \( c \) are the spring constant and damping ratio, respectively. We would like to note that the spring and damping terms add some complexity, but are necessary to guarantee system stability for computation of the Controllability Gramian.

This immediately offers two ways to assess how the controllability of the system changes. First, we can consider how the necessary control energy to move the mass back to the origin changes with different amounts of allowable time \( t_1 \) for some fixed \( \theta \). Second, we can consider how the controllability of the system changes as \( \theta \) changes.

3.1. Controllable Directions

We first investigate how the “controllable directions” of the system change as \( \theta \) changes. Intuitively, one would suspect that the most controllable direction (\( v_1 \) in (6)) shifts from the diagonal towards the x-axis as \( \theta \) increases. Figure 3 highlights this behavior.

Figure 3. The most controllable direction of the mass-spring-damper system for three values of \( \theta \).

Each line in Figure 3 is a unit vector representing the most controllable direction of the system, projected onto the x-y plane. The most controllable direction can be interpreted as the direction in which
the system can move one unit using the least amount of control energy. Notably, in this two-dimensional example, both the position and velocity act in the same cartesian direction. When \( \theta \) is small, this direction is just less than 45° from the horizontal. As \( \theta \) increases, and the effect of actuation in the y-direction is diminished, the most controllable direction shifts to be closer to the horizontal.

3.2. Fixed \( \theta \)
A slightly different interpretation of the controllability of the system is also useful - we consider the necessary control energy to move the mass to the origin from an initial position \((X_0, Y_0)\) within a finite amount of time \(t_1\). In this example, we define the origin to be when every state of the system is equal to zero. As the time constraint \(t_1\) is shortened, the forces \(F_1\) and \(F_2\) must be greater in order to move the system faster. Figure 4 shows the amount of control energy to move the system from any point within a grid on the surface to the origin in \(t_1 = 18, 20, \) and 22 seconds.

![Control Energy to Return to the Origin (N^2s)](image)

**Figure 4.** Control energy to return the point-mass to the origin from an initial position \((X_0, Y_0)\). For all three cases, \(\theta = 0\), but the time horizon \(t_1\) is changed.

In Figure 4, \(\theta = 0\) in all three cases. The results are as expected: in all cases, the necessary control energy to move the system back to the origin is related to the distance from the origin. Additionally, as we lengthen the time for the system to return to the origin, less control energy is needed. Here, control energy is simply the work done by the forces \(F_1\) and \(F_2\). For more complex systems, the results may not be as intuitively easy to predict, but this control energy analysis can still be performed to provide some understanding of the system capabilities.

3.3. Changing \( \theta \)
Similarly, we can fix the amount of time \(t_1\) to return the mass to the origin, but change the value of \( \theta \) (shown in Figure 2). Figure 5 compares the control energy for three values of \( \theta \). Unsurprisingly, when \( \theta = 45° \), the upper-left and bottom-right most corners of the studied space demand the most energy to return the mass to the origin. As \( \theta \) becomes smaller, the necessary control energy to return to the origin decreases, and when \( \theta \) becomes larger, it becomes increasingly more difficult to return the system to the origin for increasing values of \(|y|\). Notably, when \( \theta = 90° \), the system is no longer controllable and \( W_c \) loses rank.

4. Floating offshore wind turbine applications
The basic principles discussed in Section 2, which were illustrated on a simple planar point-mass system in Section 3, can be applied to floating wind energy systems. Here, we apply the analysis for the
Figure 5. Control energy to return the point-mass to the origin from an initial position \((X_0, Y_0)\). In all three cases, \(t_1 = 20\) s, but the angle \(\theta\) by which \(F_2\) acts on the system is changed.

DTU 10MW wind turbine, where we consider the two floater concepts defined as part of the LIFES50+ project [9]. A brief overview of some of the primary properties of interest for the two turbine platforms, the NAUTILUS-10 and OO-Star Wind Floater, are presented in Table 1. The rotational hydrostatic restoring stiffness for the OO-Star Wind Floater is negative, signifying that it is unstable without a turbine on the platform. Additionally, the OO-STAR Wind Floater substructure includes an active-ballast system that is considered to be full for this analysis. We also note that the authors of [9] modified the DTU 10MW wind turbine tower slightly to be more suitable for floating offshore applications. Figure 6 shows a generic schematic of a wind turbine on a floating semi-submersible platform.

Using OpenFAST [7] linearization capabilities, linearized models of the DTU 10MW wind turbine on the LIFES50+ NAUTILUS-10 and OO-Star Wind Floater platforms were found. The models were linearized in steady-state operating conditions at 14 m/s steady inflow wind and calm water. The inflow wind has a vertical shear with the standard power-law wind profile with an exponent of 0.14, which is typical of stable offshore wind conditions [10]. We assume standard collective blade pitch and generator torque actuation. A simplified linearized model is used in this initial study. The generator speed and platform degrees of freedom are considered. We note that the platform horizontal surge translational displacement, sway translation displacement, and rotor angular displacement states are removed due to their instability. The system must be a stable system in order to calculate the standard form of the Controllability Gramian. This results in an 11th-order system with the following states:

- Platform vertical heave translation (m)
- Platform roll tilt rotation (deg)

Table 1. A few relevant parameters for the NAUTILUS-10 and OO-Star Wind Floater substructures. The reference point for the hydrostatic stiffness parameters is the origin. The active ballast system in the NAUTILUS-10 is considered to be full.
Figure 6. A diagram of a floating offshore wind turbine on a generic semi-submersible wind turbine platform. Here, $\theta_p$ is the platform pitch angle, and $\theta_r$ is the platform roll angle.

- Platform pitch tilt rotation (deg)
- Platform yaw rotation (deg)
- First time derivative of platform horizontal surge translation (m/s)
- First time derivative of platform horizontal sway translation (m/s)
- First time derivative of platform vertical heave translation (m/s)
- First time derivative of platform roll tilt rotation (deg/s)
- First time derivative of platform pitch tilt rotation (deg/s)
- First time derivative of platform yaw rotation (deg/s)
- First time derivative of variable speed generator (deg/s)

To illustrate the ideas of controllability of FOWTs, we focus this study on the energy to control the platform pitch and roll rotational motions using collective blade pitch and generator torque actuation only. Though these are not the only dynamics of concern for a FOWT, they are easily tractable as a proof of concept and introduction to the application of controllability analysis to FOWT systems. The consideration and direct analysis of the other dynamics of the system will be included in future developments of this work.

In an attempt to equally consider the effect of blade pitch and generator torque actuation, we introduce normalization terms. We normalize the blade pitch angle input by the average steady-state variance in blade pitch angle, 1.4817 deg, to a 1 m/s wind speed change. Similarly, we normalize the generator torque input by the average steady-state variance in generator torque, 25674.877 N, to a 1 m/s wind speed change.

4.1. Controllable Directions

A similar controllable direction analysis to that presented in Section 3.1 is considered for a FOWT. Rather than comparing changes in $\theta$, as was done in the point-mass example, we compare how the controllability in the pitch and roll direction changes for the DTU 10 MW wind turbine on the NAUTILUS-10 and OO-Star Wind Floater platforms.

Figure 7 shows this controllability comparison, where even though the state of the linearized model is 11th order, we choose to investigate the differences of controllability in the platform pitch and roll
directions only. The lines in Figure 7 show the pitch and roll components of the vector \( v_1 \) projected onto a two-dimensional plane. The magnitudes of these directions are significantly less than one because the generator speed is the most controllable state by a substantial amount. Unsurprisingly, the pitch direction is far more controllable for both of the platform types. This metric does suggest that the OO-Star Wind Floater is more controllable in the roll direction, however.

**4.2. Time to vertical position**

A study comparable to that shown in Section 3.2 was also done for the DTU 10MW wind turbine on the LIFES50+ NAUTILUS-10 semi-submersible platform. We consider the control energy to return the system to a neutral, vertical position (\( \theta_p = \theta_r = 0 \)) from some combination of \( \theta_p,0 \) and \( \theta_r,0 \). For simplicity, we define the rest of the platform states to have zero initial and final conditions. We consider three different time horizons: \( t_1 = 2, 2.5, \) and \( 3 \) times the once-per-revolution period of 6.25 seconds.

**Figure 8.** Comparison of control energy necessary to return the platform to vertical from small non-vertical initial conditions. The study is done at three different time horizons \( t_1 \), where \( T \) denotes the once-per-revolution period of 6.25 seconds of the turbine.
In Figure 8 we see that the necessary control energy decreases as we allow more time, which follows the expected trend. The result also shows that it is significantly easier to control the platform pitch in the fore-aft direction than it is to control the platform roll in the side-side direction. This is not a surprising result, as the thrust of the turbine rotor is changed by both blade pitch and generator torque actuation, and hence directly affects the fore-aft platform motions. A useful result from this analysis is an improved understanding of what a realistic or desirable time scale to control the platform pitch might be, at least from a control energy perspective.

4.3. Platform Comparison
Another useful study is to compare the control energy for the same wind turbine, on two floating platforms. This is somewhat analogous to the example in Section 3.3. In the simplified point-mass example, we changed the angle of $\theta$ which changed the dynamics of the system. Here, we compare an aspect of the controllability of the DTU 10MW wind turbine on the LIFES50+ NAUTILUS-10 and the OO-Star Wind Floater, each designed to have a different dynamic response. Figure 9 shows this comparison of the control energy necessary to return the platform to vertical.

![Figure 9. Comparison of control energy necessary to return the DTU 10 MW wind turbine on the NAUTILUS-10 and OO-Star Wind Floater platforms to vertical from small non-zero vertical initial conditions. Both turbines are given two times the rated rotor rotational period to return to vertical: $t_1 = 2T$, where $T = 6.25$ s. Notably, the results for the NAUTILUS-10 are the same as those in the left-most plot in Figure 8 shown on a different color scale.](image)

In both studies, we allow the simplified turbine two times its rated once-per-revolution period to use collective pitch and generator torque control to return the platform to vertical. Interestingly, we see differing results for each FOWT model. For small displacements, the differences are minimal. However, displacements in the platform roll take more energy to stabilize in the OO-Star Wind Floater platform model than in the NAUTILUS-10 platform model. This is unsurprising given the OO-Star’s larger mass and inertia.

5. Discussion
The extent of the utility of this Controllability Gramian analysis goes further than the results shown here. The ideas presented within the context of a simplified example system and two FOWT models form a foundation for other studies.

In this analysis, some states were removed due to known unstable dynamics. Through basic knowledge of the system, we know that the rotor azimuth position will continue to grow and is thus unstable. Further analysis shows that other states, such as the platform yaw and translational motions, are very weakly controllable or unstable as well. These states can result in very poor conditioning of $W_c$ and can cause numerical instabilities in the standard tools employed in MATLAB [11]. As a wind
turbine and platform designer, a goal to increase the controllability of these weakly controllable modes may prove useful for increasing system performance.

As discussed in Section 2.2, the singular values of \( W_c \) correspond to the controllable “directions” of the system. Analysis of these directions and their associated singular values could offer valuable insight into the controllability of the system. We know that the most controllable direction \( v_1 \) of a FOWT is generally far more controllable than any other direction. Consideration of how this direction changes between system designs offers a comparison of system dynamics from a controls perspective. Additionally, the magnitudes of the singular values \( \{ \sigma_2, \ldots, \sigma_n \} \) are useful to consider how controllable the system is as a whole, outside of the most controllable direction. An increase in some singular values of \( W_c \) would indicate more controllability in directions other than \( v_1 \), while an increase in the smallest singular value \( \sigma_n \) would indicate a more controllable system as a whole.

Extensions of the initial studies presented in this work could also provide valuable information for the wind turbine controls engineer and system designer. Figure 9 shows us that more control energy is needed to move the system state back to neutral for the OO-Star Wind Floater platform within the prescribed amount of time. The amount of time and control energy it takes to return the system to its neutral state is certainly dependent on the platform’s hydrostatic stiffness and damping. These design parameters, along with platform mass and inertia, are some of many design decisions made that directly affect the system dynamics. The desired time to move the system is also dependent on the initial state in question and could additionally inform platform designs. Considering these controllability metrics in platform development stages could provide an additional design parameter. This idea is, of course, not limited to wind turbine platform design. A control energy analysis to move the state to any \( x_{des} \) is possible for any stable system.

Another study of interest is a comparison of controllability with different types of actuation. It was found that, for the DTU 10MW on the NAUTILUS-10 platform, the necessary control energy to move the system state to neutral in the same study done in Section 4.2 was significantly decreased using individual pitch control versus collective pitch control. Within 2 degrees of allowable pitch and roll motion, the highest minimum control energy needed to return the turbine to neutral within two rotational periods was decreased by nearly 5 orders of magnitude. A further extension of this study would be the inclusion of different types of actuation to assess their potential impact on the control system.

The results of a controllability analysis is, of course, limited to the context of the control theory applied in the analysis. It should be noted that a result of “less control energy” does not necessarily equate to “better”. Especially within the context of minimal energy control, metrics such as structural loads, feasibility, and basic practicality are not directly accounted for. The authors suggest that a study such as this should be an initiation to a larger, more extensive study, or that the obtained metrics be used in addition to other metrics in an optimization. The wind turbine design space can tend to be fairly limited and includes the balancing of many gains and trade-offs - controllability and control energy are simply two types of metrics that could be used to encourage controls co-design of floating offshore wind turbines.

6. Conclusion

In this work, theoretical control systems analysis methods have been introduced as a tool to help understand the dynamics of floating offshore wind turbines. Study of the Controllability Gramian offers multiple metrics that can be considered in a controls co-design process.

A simple point-mass model was presented in order to establish the modern control theory concepts within an accessible physical context. We then extended the ideas to a control energy analysis of floating offshore wind turbines. Figures 8 and 9 show some initial results of this analysis. We quantified the control energy necessary to move a simplified floating wind turbine model to a neutral, vertical position from some non-zero rotational displacements. This control energy metric was considered for different allotted amounts of control time and for two different floating wind energy systems.

A discussion of potential uses and extensions provides a number of future research avenues. Results
from this analysis could better inform structural design constraints and add to the controls co-design
toolbox. The presented methods of analysis offer a way to consider the controller before any time-
domain simulations with an implemented controller are run. This provides the opportunity to increase
the pace of the wind turbine design cycle. Additionally, the analysis offers another metric to potentially
aid convergence for optimizers in systems engineering tools such as WISDEM [12].

Finally, an entirely separate, but parallel study could be done for the observability of the wind turbine
system. The consideration of different sensors to be used could better inform the choice of feedback
signals for the controller. Through better observability, knowledge of the system state can be improved,
and the ability to design more complex or better-tuned controllers is made possible.

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