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Study of Vibration Reduction of Offshore Wind Turbines

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ABSTRACT

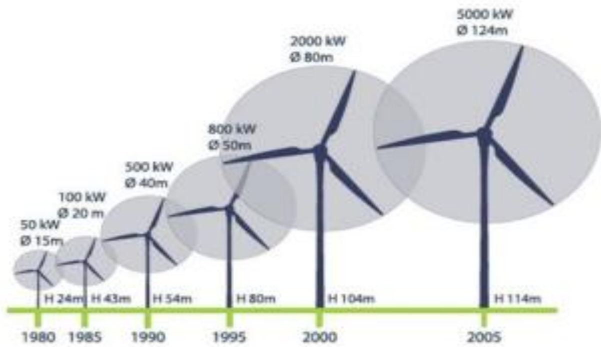
Wind turbines are becoming an accepted method for generating electricity. With technology advancements and mapping of the global wind resource, offshore locations are now utilized for turbine placement due to their strong and consistent winds. Though these offshore areas offer high power density values, the environmental conditions in these locations often impose high wind and wave forces on offshore wind turbines (OWTs) making them susceptible to intense loading and undesirable vibrations. It has therefore become necessary to utilize mechanical techniques for making OWTs more adapted to external conditions. One method to reduce system vibrations is through the use of structural control devices typically utilized in civil structures. Among the many types of structural control devices, tuned liquid column dampers (TLCDs) show great promise in the application to OWTs due to their high performance and low cost. This thesis examines the use of TLCDs in a monopile as well as floating barge and spar buoy OWTs. Equations of motion for limited degree-of-freedom TLCD-turbine models are presented. A baseline analysis of each OWT is performed to generate a quantitative comparison to show how a TLCD would affect the overall dynamics of the system. The iv models are then subjected to two methods of testing. The first is an initial perturbation method where the tower is displaced and allowed to oscillate according to the structural and environmental conditions. The second method subjects the system to realistic wind and wave thrusting functions. Optimal TLCD dimensions are derived for the models using a deterministic sweep method. The TLCD configurations examined include those with a uniform and non-uniform column cross-sectional area. In most cases, the TLCD is shown to successfully reduce overall tower top displacement of each of the OWTs as well as the platform pitch when applicable. In some cases, use of the TLCD actually increases overall tower and platform motion. This thesis also examines the use of idealized tuned mass dampers (TMDs) in OWTs when utilized in the modified aero-elastic code, FAST-SC. Comparisons between the optimized TLCD and the idealized TMD are made with regards to motion reduction and damper parameter values.

INTRODUCTION

With increasing energy demands and the depletion of the earth's fossil fuels, wind turbines have become a viable and cost-effective means for producing electricity. Wind energy development can offset fossil fuel usage and impact the global energy portfolio. Offshore locations offer outstanding wind conditions for wind turbine energy generation because of high and consistent wind speeds, lower intrinsic turbulence intensities, and low shear [20]. These conditions result in significantly increased turbine capacity factors compared to onshore locations [11]. Although the wind resource is advantageous, developing offshore wind energy also presents a number of challenges. As technology has progressed over the years, offshore wind turbines (OWTs) have become larger in size and are being placed in deeper waters. OWTs will subsequently be subjected to harsher external conditions including high wind, wave, current, and possibly ice forces. This results in increased system-wide dynamic loading on the structures. These forces create undesirable vibrations in the structure, which reduces the fatigue life of the wind turbine. As a result, tower construction costs, operation and maintenance, necessary material and the overall cost of energy will increase in offshore scenarios [4].

Background

Over the past 40 years, onshore wind turbine development has increased due to the need for renewable energy production and technology advancement. In more recent years, wind turbines have been placed in offshore locations where the winds have lower turbulence and higher, more consistent speeds compared to most onshore locations. These locations provide a higher amount of possible energy extraction.As technology has progressed over time, wind turbine size has also increased to capture more of the wind's energy. This is because the power captured by a wind turbine is proportional to the swept area of the rotor. The growth of wind turbines has generally led them to be placed in offshore locations due to the undesirable noise production and possible visual burden in an onshore area. Placing the turbines in offshore locations can diminish the possibly disturbing effects that they may have on the local population. A larger rotor size also experiences increased dynamic and stochastic loading. Less turbulence in offshore locations provides conditions that are more suitable for larger wind turbine rotors.



Year-to-year growth of wind turbine height and rotor diameter

STRUCTURALCONTROL

Necessity for Structural Control Devices

Though wind energy has progressed greatly over the past 40 years, there are still many obstacles to overcome, especially in the offshore industry. Overall cost of energy is a huge factor in the placement and construction of OWTs. One area that can be improved upon is the structural vibration control of the turbine, tower and support components. Due to their large size and complexity, it is necessary to reduce the costs of OWTs by making them both more efficient and increasing overall fatigue life. One method for reducing unwanted vibration due to loading is to apply a structural control device. Structural control has been used extensively in civil structures such as buildings and bridges to offset seismic and wind induced vibrations. This involves installing a mechanism in a civil structure that will effectively reduce force-imposed excitation and increase the overall fatigue life of the system. OWTs offer an interesting opportunity for utilizing a structural control device. High dynamic forces can occur in OWTs due to wind, wave, and possibly ice loading. As wind turbine size continues to grow, the loading placed on a turbine will also increase. OWTs have the potential to benefit structurally from the use of vibration-damping mechanisms such as those presented in the following sections.

Overview of Structural Control

Structural control systems are used to mitigate unwanted vibrations that are induced on the main system. They can be designed in a number of forms. Active and semi-active systems utilize feedback control to improve the vibration reduction of a 12 structure. Passive systems are typically tuned to a certain frequency of a particular structure for vibration mitigation. This thesis will only examine passive structural control devices as the method for reducing vibrations in OWTs.

DESIGN CRITERIA AND CHALLENGES

Examining Design Challenges

Each type of control device has its own benefits and drawbacks. Many design challenges are considered when assessing the pros and cons of each system in order to obtain an optimal system for OWTs that will generate the lowest cost of energy. The following section will outline some potential concerns for choosing a damper system for an OWT. A final decision is then made regarding a specific damping device.

System Costs

One of the most important considerations in this thesis is deciding upon a vibration reduction system that will minimize fatigue loading while reducing overall cost.

Costs that need to be considered for placing a structural control system in a floating wind turbine can include capital costs, installation, maintenance, and decommissioning. Maintenance on the turbines can become extremely costly due to the accessibility, restrictions imposed by weather, and the necessity for specialized service vessels.

Maintenance and Replacement

There are many difficulties associated with accessing and maintaining a damper system in a wind turbine nacelle or platform. Accessibility and maintenance in a tall wind turbine or underwater location can prove difficult. A damper system needs to be chosen that will minimize the amount of required maintenance while not sacrificing efficiency. Some types of damper systems, including the metallic yield damper require replacement after every impacting seismic event.

Performance

Many of the noted structural control devices are designed to react to extreme loading. Metallic yield and friction dampers are designed more for extreme events such as earthquakes. The nature of the wind and wave forces imposed on an OWT is not typically as extreme as an earthquake. TMDs are specifically designed for this type of vibration reduction. Specialized TLCDs are shown to be even more effective than TMDs in particular cases. One positive aspect of the TLCD is that unlike other types of TMDs, they can dissipate very low amplitude excitations and are consistent over a wide range of excitation levels [23]. This gives them the ability to damp vibrations other than that of the natural frequency to which they are tuned and are more applicable to an OWT.

TLCD COUPLING TO OFFSHORE WIND TURBINES

Baseline Wind Turbine

In order to approximate the properties of a wind turbine for use in the simulations, a baseline turbine model is used for analysis. The turbine chosen is the widely-studied NREL 5 MW wind turbine model.

Turbine Limited DOF Model Development

Stewart has developed limited DOF equations of motion for the monopile as well as the three previously noted floating OWTs [24]. Stewart's research involved the use of an idealized TMD when placed in varying locations of a specific turbine to reduce displacements and fatigue. In this chapter, Stewart's equations describing the motion of the monopile, barge and spar buoy with an attached TMD are modified to include the use of a TLCD. The TLCD-wind turbine structure equations can be derived and used to model the motion of a wind turbine with attached TLCD in a simplistic, yet realistic and time-efficient manner**.**

Monopile

Stewart's equations for the two degrees of freedom of concern (the rotational tower bending DOF and the translational TMD DOF) are used for analyzing the motion of the monopile. The developed model similarly contains two degrees of freedom: a tower bending DOF and a TLCD DOF. The tower is modeled as an inverted pendulum with rotary damping and stiffness in the tower base. Due to the nature of the monopile, it is only logical to place the damper system in the nacelle. The limited DOF model for the monopile coupled with a TLCD in the nacelle is shown in Figure 6.1. The t subscript and the TLCD subscript represent the tower and tuned mass damper DOF, respectively. m, k and d are the mass, stiffness and damping of each system, respectively. It is noted that the mass of the rotor-nacelle assembly (RNA) is included in the tower mass. θ represents the rotation of the system in degrees while the over dots represent time derivatives. wTLCD is the displacement of the water inside the TLCD. g is the acceleration due to gravity. Ry is the ground reaction force.

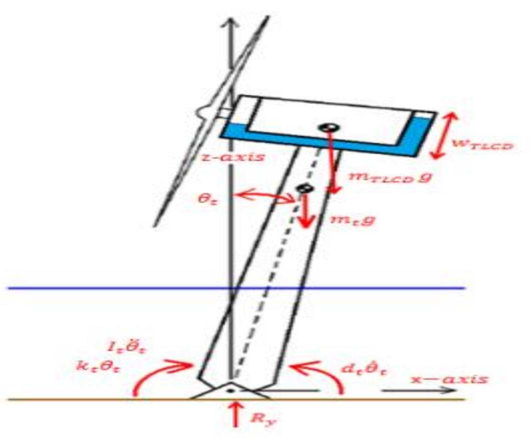


Diagram of the limited DOF monopile-TLCD model

Barge

Because the barge floats, it must be written with an additional DOF for the floating platform. The TLCD can potentially be placed in either the tower or the platform in order to examine the motion reduction capabilities. This results in two sets of equations of motion. The limited DOF model for the barge coupled with a TLCD in the nacelle and in the platform is shown in Figure 6.2. The p subscripts represent the added platform DOF.

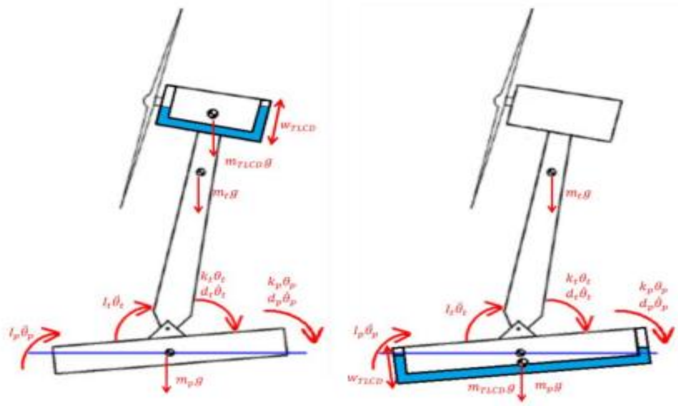


Diagram of the limited DOF barge-TLCD model with TLCD in nacelle (left) and platform (right)

OPTIMIZATION RESULTS

Organizing Results

The optimization results can be grouped according to the following: • Type of OWT (monopile, barge, spar buoy). • Location of the TLCD (nacelle, platform when applicable). • Testing method performed (initial perturbation or external force). • Non-uniform or uniform TLCD: The non-uniformity of the cross-sectional areas of a TLCD can add complexity to the construction and installation of a TLCD in an OWT. It is therefore interesting to optimize a uniform TLCD with $\alpha = 1$ and compare its effectiveness to that of a non-uniform cross-sectional area TLCD. This simplistic design approach can speed build time and increase the ease of manufacturing. • TLCD mass values: Mass ratio values of approximately 2% of a structure's overall mass are typically used when designing a TMD or TLCD. For this thesis, values that equate to approximately 1%, 2% and 4% will be used. This is done to test the effectiveness of each mass value while observing their corresponding TLCD dimensional and performance differences. When examining the monopile OWT, these values equate approximately to 10,000 kg, 20,000 kg and 40,000 kg. For scenarios when the TLCD is placed in the platform, values of 100,000 kg, 200,000 kg and 400,000 kg are used to represent approximately 1%, 2% and 4% of the platforms entire floating mass.

CONCLUSIONS AND FUTURE WORK

The TLCD is an effective type of damper system used for reducing vibrations in civil structures. It is shown that applying a TLCD to a structure such as an OWT can effectively reduce the overall motion of the structure in most scenarios, though some exacerbate the motion. The following objectives are completed within this thesis. • A methodology is generated to simulate a TLCD-OWT system. EOMs are derived for a limited DOF system for three different OWT configurations, which include various locations for the TLCD. Through the use of a deterministic sweep optimization routine, dimensions are generated for the TLCD. Simulations are successfully performed to output the motion of the TLCD-OWT coupled system in the time domain and the realistic motion of the OWT can be observed. • Results show that optimally sized TLCDs (within defined constraints) can potentially reduce the vibration of an OWT. It is also shown that the use of an optimized TLCD sometimes provides no benefit to the structural motion of a system. When a TLCD is utilized in an OWT and the results are favorable based on the analysis presented in this thesis, increased fatigue life of the wind turbine and support structure as well as reduced overall cost of energy can potentially be achieved. • Results show that using a non-uniform cross-sectional area TLCD typically outperform one with a uniform cross-sectional area by shortening the TLCD's length requirement. • Quantitative comparisons are also made with an optimal TMD. It is shown that optimized TLCDs and TMDs have approximately the same equivalent spring valuesand natural frequencies for the monopile and barge, as they work to reduce a particular frequency of the OWT, but vary widely for the spar. TLCDs also have much higher damping values based on the constraints of the modeling analysis compared to the use of a TMD with defined stops.

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