JACKET SUBSTRUCTURE FATIGUE MITIGATION THROUGH ACTIVE CONTROL

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Abstract. As offshore wind farms are being installed farther and in deeper waters offshore, new, and more sophisticated marine substructures such as jackets need to be used. Herein, a 10MW wind turbine mounted on a jacket sub structure at a mean water depth of 50 meters is investigated with regards to the fatigue design loads on the braces of the jacket. Since large wind turbines of 10MW rating have low rotor speeds (p), the modal frequencies of the sub structures approach 3p at low wind speeds, which leads to a modal coupling and resonance. Therefore an active control system is developed which provides sufficient structural damping and consequently a fatigue reduction at the substructure. The resulting reduction in fatigue design loads on the jacket structure based on the active control system is presented.

1 INTRODUCTION

Offshore wind turbine support structures are migrating to moderately deeper water depths of 40m to 50m presently and thereby the usage of jackets structures has gained relevance. However, the loads on the support structure are made more complex rendering the impact of present loads prediction models more uncertain [1]. Loads simulation on offshore wind turbines utilizes aeroservoelastic solvers that compute the loads on the rotor and support structure using fully coupled equations of motion [2]. The predominant external loads on the wind turbine are due to the turbulent Wind, irregular waves and the interaction of the rotor control system with the environment.

Jacket sub structures are frame type structures consisting of tubular steel members connected by welded joints. The design of jacket members are strongly influenced by fatigue loads [3]. The magnitude of fatigue is mostly governed by the normal operation of the wind turbine especially under the influence of wakes which result in increased turbulent loading. Also the effect of hydrodynamic loads on the jacket members cannot be ignored. Sea states possessing large significant wave heights, nonlinear behavior with peak periods close to the jacket natural frequency can also induce large fatigue. The support structure natural frequency is usually designed to be below 3 times the rotor speed (3p). For constant blade tip speeds, up scaling of wind turbines results in slower rotation of rotors as wind turbine rotors increase from 100m towards 200m. This results in strong excitation of the support structure by the rotor at wind turbine start-up and during operation at low wind speeds. Since the annual distribution of mean wind speed at speeds near 6m/s has a finite probability, this results in increased fatigue of jacket joints. Jacket sub structures being stiff by design may not be designed to have low frequencies below 3p excitation for large wind turbines and therefore the excitation of the sub structure needs to be dissipated using active control.

The wind turbine control system is usually governed by generator torque control in the variable speed region of operation and blade pitch control beyond rated wind speed. It is also possible to have supervisory pitch control in operating regimes just before rated wind speed. In the present paper the generator torque control is modified to mitigate the excitation of the jacket at low wind speeds and also mitigate the side to side excitation through active drive train damping.

2 WIND TURBINE MODEL

The wind turbine model used in this investigation is an upwind, variable speed pitch controlled three-bladed offshore machine with the rated power of 10 MW; for more details see [4]. The wind turbine is installed on a jacket at 50 meters of water depth and has a hub height of 119 meters, which gives 89 meters of tower length and 76 meters of jacket substructure. The jacket to tower-base interface is considered stiff and is neglected. The jacket is considered rigidly connected to the sea bed and therefore jacket's piles and soil effects are also neglected. The wind turbine's aero-servo-elastic model was implemented and all simulations were performed in the HAWC2 aeroelastic code [5, 6]. The normal operation of the wind turbine was simulated using design standard IEC 61400-3 load case DLC 1.2 under class 1A conditions and using the Mann wind turbulence model as input. A normal sea state and mild significant wave height was assumed, whereby the primary design driver was assumed to be the interaction of the rotor with the turbulent wind.
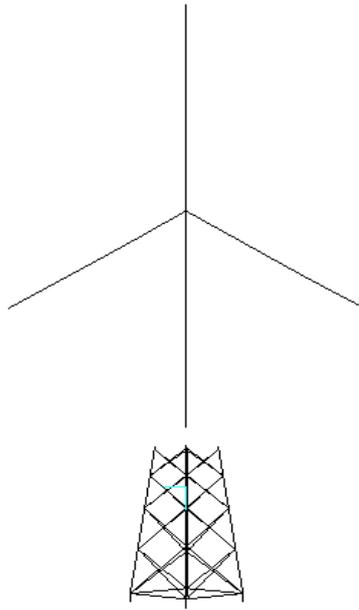
Figure 1: Offshore wind turbine beam model (HAWC2)

3   CONTROL SYSTEM

The introduction of advanced wind turbine machines and structures raises demand for more sophisticated control systems. The main goal of a wind turbine control system is to maximize power yield in the variable speed region, maintain rated power above rated wind speed and economic efficiency. However, with larger and more complex wind turbine structures, it is important to enhance and support structural design with active structural controllers and dampers. Such a system will significantly increase structural integrity, avoid possible structural excitation and prevent structural resonances, providing the opportunity for mass/cost saving and new concepts. The control system objectives (power production and structural control), mechanisms (generator torque and collective pitch angle control, see Figure 2) and design process itself can be addressed separately in a hierarchical manner, as shown in the following sections.
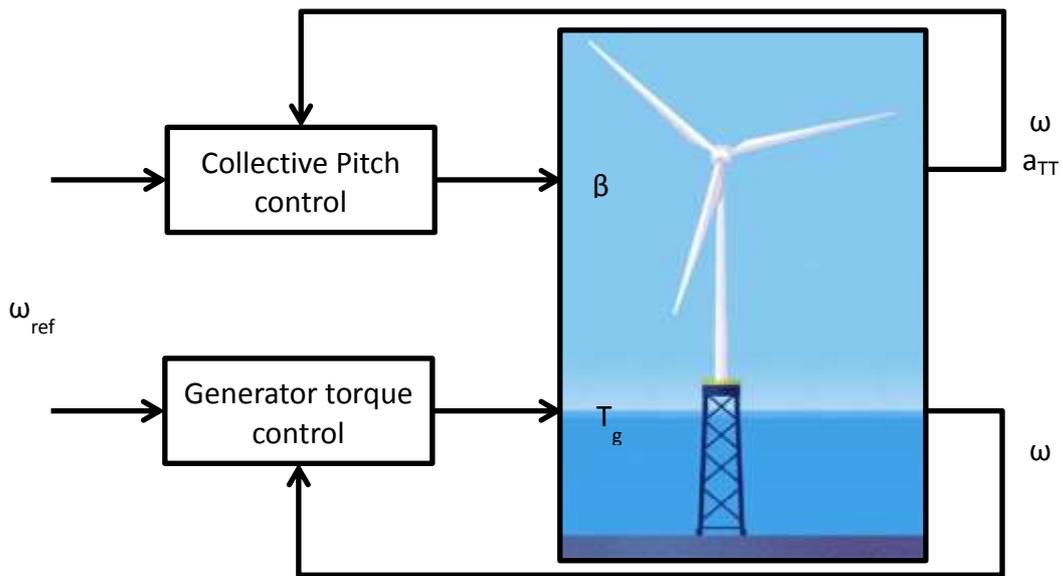
Figure 2: Wind turbine control system

3.1 Power production control system

The power production of wind turbine is controlled by a generator torque controller (see Figure 3, black part) and a collective blade pitch angle controller (see Figure 4, black part). Both control systems are based on PI type controller, where the angular rate of the generator is the only signal measured.
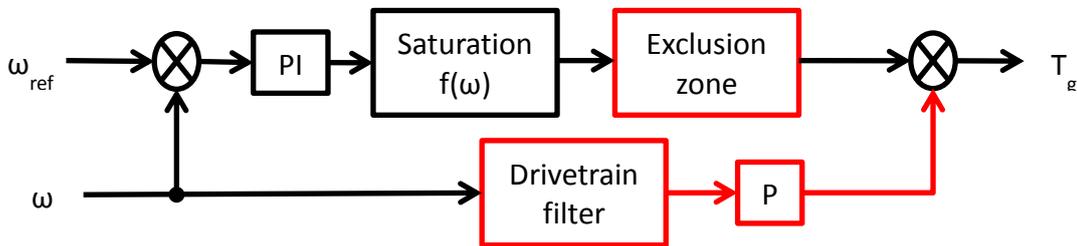

Figure 3: Generator torque control system (black - Power control, red – structural control)

The saturation of the generator torque signal depends on the operational regime and provides the functionality of optimal Cp tracking (at variable speed regime) and generator power stabilization (at constant speed regime).
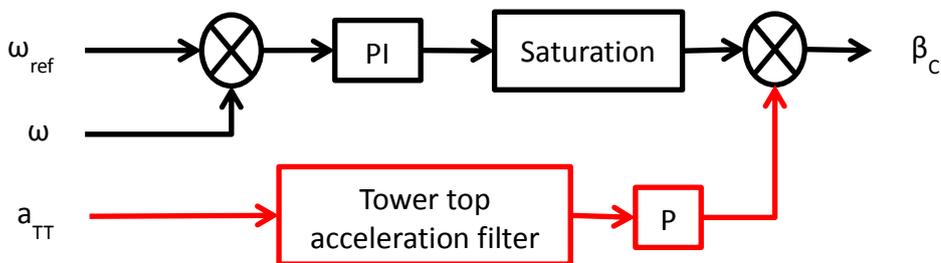

Figure 4: Collective pitch control system (black - Power control, red – structural control)

The main goal of a power control system is to guarantee the maximal power production. Such criterion can be expressed by a steady power curve (see Figure 5), where the dependency of the power production on wind speed is presented (only mean wind speed is considered). Alternative measure is the mean annual power yield of wind turbine (see Figure 6).
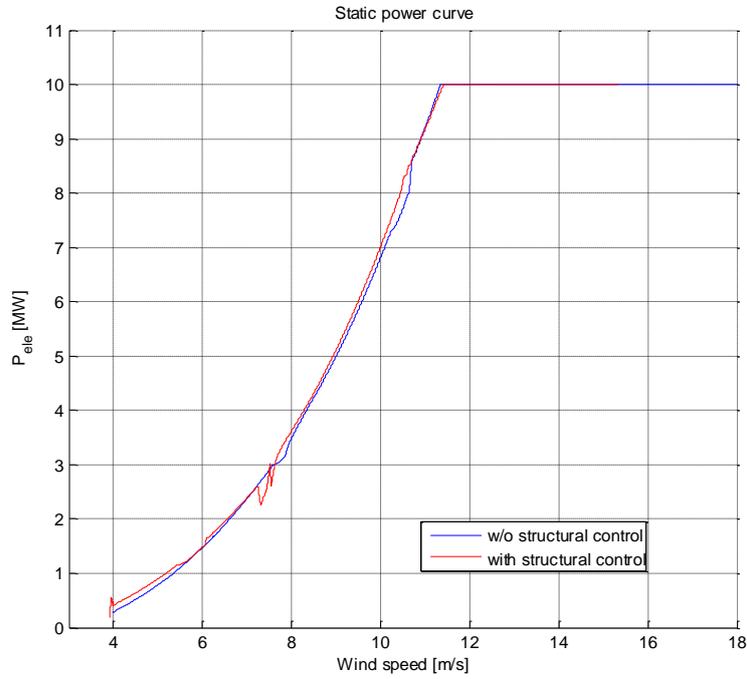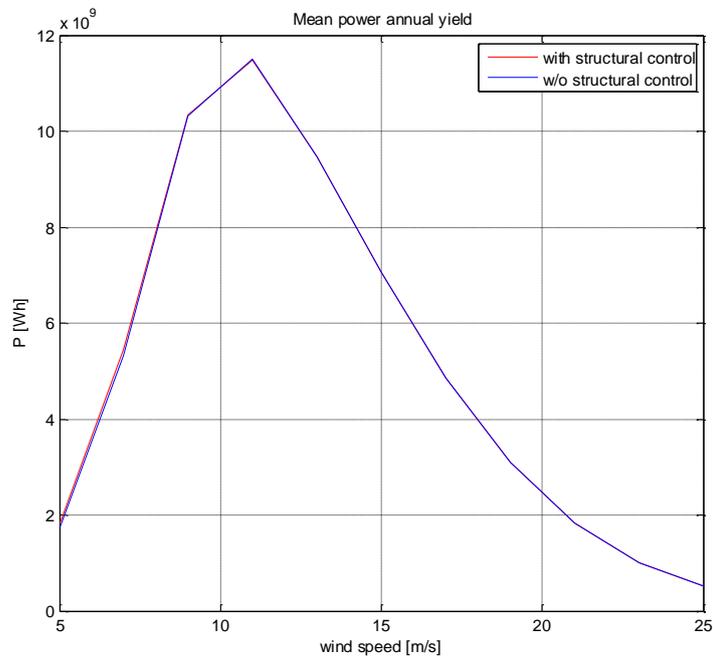

Figure 5: Static power curve

Figure 6: Power annual yield (using Weibull spectra)

The hierarchical structure of the control system provides the benefit of modular design in separated steps, but also the disadvantage of the imperative to preserve the control design objectives as decoupled. The negligible impact of structural control on the power production can be seen from Figure 5 and Figure 6.

3.2 Structural control

The structural control system is developed and implemented on top of the power production controller. The main components of the controller are presented in Figure 3 and Figure 4, as shown in red parts. Main functionalities of the presented control system are the wind turbine drivetrain damper, the 3p exclusion zone and the tower top fore-aft motion damper.

The objective of the drivetrain damper implemented through generator torque control is to reduce the main shaft torsional oscillations, as otherwise, the drive shaft structure being lowly damped gives rise to severe and sometimes even unstable torsional oscillations of the drivetrain, see Figure 7. Such a dynamic loading of the drivetrain would significantly reduce its lifetime or even make the wind turbine operation unfeasible without active control.
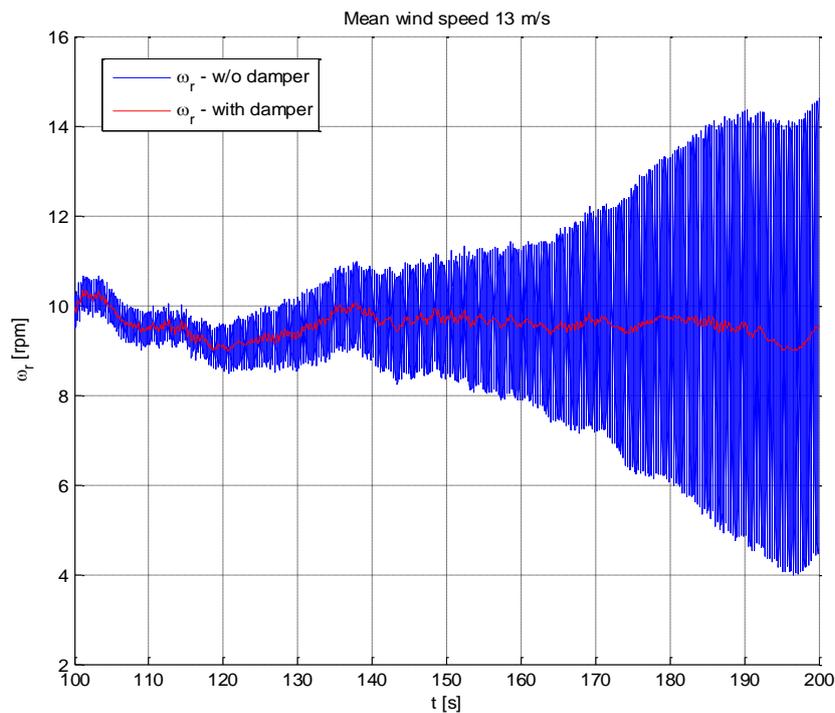
Figure 7: Drivetrain damper performance in preventing unstable torsional oscillations

The 3p exclusion zone functionality prevents substructure resonance excitation caused by the collocation of rotor 3p frequency (for particular rotor angular speed) with substructure first side-to-side and fore-aft bending modes. The main idea is to avoid rotor operation at the critical angular speed, using generator torque. The exclusion zone functionality can be seen

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from Figure 8. The rotor critical angular speed that excites the support structure first natural frequency is located at 6 rpm, therefore the generator torque control is used to keep lower angular speed lower (5.5 rpm) or higher (6.5 rpm) to avoid structural resonances. Tower top side-to-side acceleration is used as a measure of the wind turbine foundation substructure excitation here. In this case, up to 50% reduction in the tower top acceleration can be seen from Figure 8.
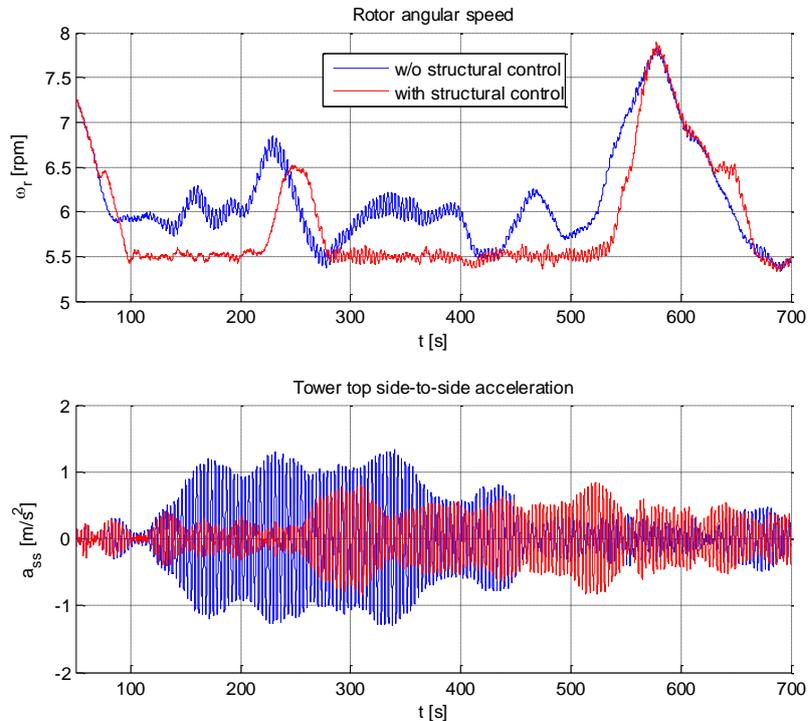

Figure 8: Exclusion zone performance

4   LOAD EVALUATION

Finally, an evaluation of the foundation sub-structure load is presented to demonstrate the capabilities and robust performance of structural control. The main uncertainty of the design and validation model is defined by variations in the wind turbine properties over full operational envelope. The considered mean wind speed variation is uniformly binned over the wind turbine operational range (5m/s up to 25m/s of mean wind speed with a 2m/s step). Normal Wind turbulence with six different initial seeds were considered for every mean wind speed. The mean wind speed is assumed to be Rayleigh distributed (i.e. Weibull distribution with an exponent of 2). It is essential for any control system implemented on a turbine to either be robust with respect to design uncertainty or be gain-scheduled over different operation points to meet robust performance requirements.

Based on previous analysis, the fatigue loading of foundation substructure seems to be the main challenge of jacket type design, therefore the fatigue equivalent damage moments were evaluated at important jacket locations, namely at tower base (see Figure 9) and K-braces (see Figure 10) based on the design Stress-Cycle (S-N) curves for steel structures . A significant

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overall fatigue reduction of up to 30% at the tower base and up to19% at jacket K-braces for side-to-side motion (M_y moments in Figure 9 and M_x moments in Figure 10) has been achieved, reaching even higher values for low wind speeds. The significant fatigue loading at wind speed of 6 m/s is caused by resonance of foundation structure with rotor 3p frequency, which reduction is accomplished by the exclusion zone functionality and its capability to avoid such a resonance respectively.
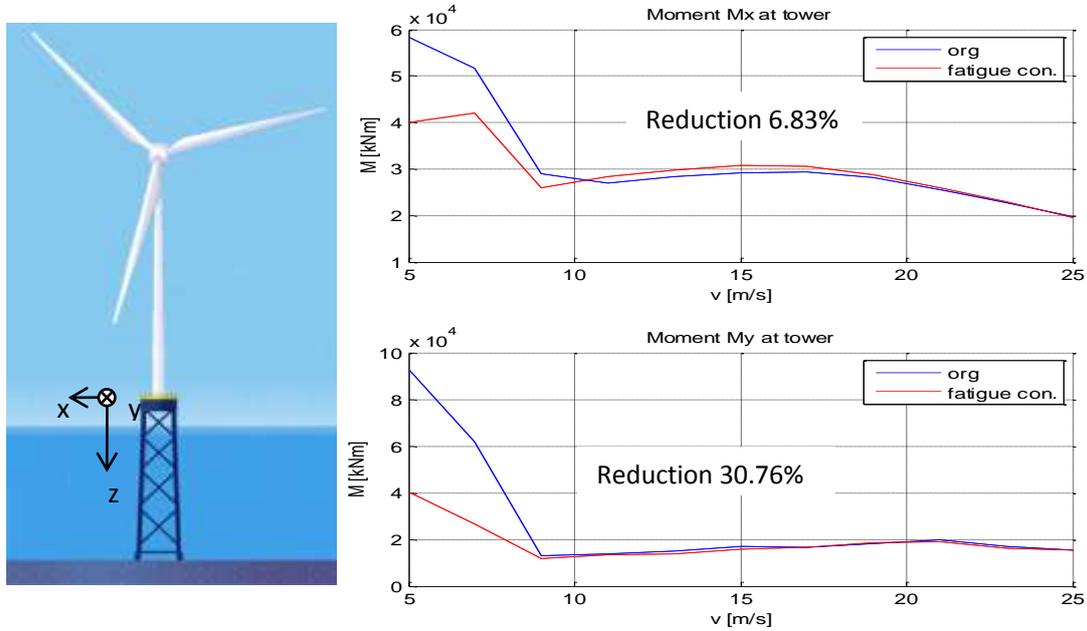

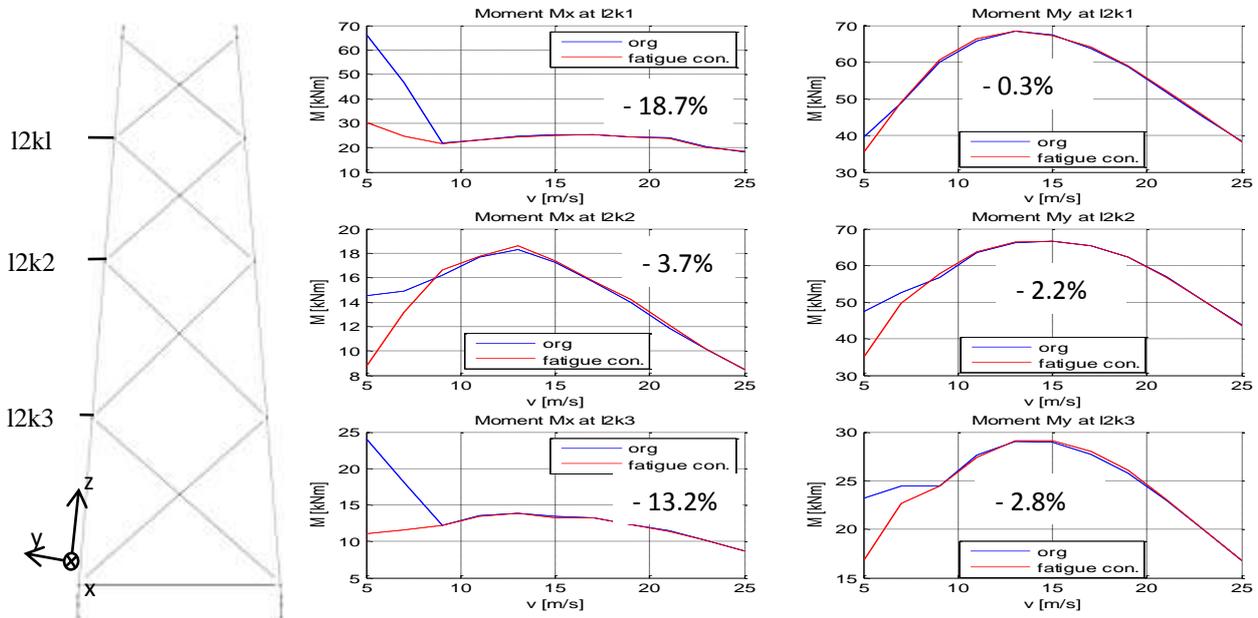**Figure 9:** Tower-base damage equivalent moments (using Weibull distribution)

Figure 10: Jacket K-joints damage equivalent moments (using Weibull distribution)

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5 CONCLUSIONS

An augmented wind turbine control system has been introduced for a 10 MW offshore wind turbine whereby fatigue loads on the sub structure may be significantly reduced. Controller robust performance has been evaluated by presenting the fatigue level reduction (overall reduction up to 19% over several operational conditions) at the critical foundation substructure locations, namely K-braces. The presented novel control approach gives the possibility to significantly reduce the sub structure mass and therefore cost savings.

Acknowledgement

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