INDIAN INSTITUTE OF TECHNOLOGY GUWAHATI
SHORT ABSTRACT OF THESIS

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Thesis Title: **Shape Memory Alloy Based Stiffening of Horizontal Axis Wind Turbine Blade for Vibration Control and Fatigue Life Enhancement**

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Thesis Submitted to the Department/ Center	:	**Civil Engineering**
Date of completion of Thesis Viva-Voce Exam	:	**26-07-2021**
Key words for description of Thesis Work	:	Shape memory alloy, Wind turbine, Semi-active tendon, Smart material, Longitudinal stiffening, Fatigue analysis

SHORT ABSTRACT

The last few decades have witnessed a tremendous increase in energy demand to support global socioeconomic development. The worldwide climate change and depleting fossil fuel with ever-increasing carbon footprint have forced humankind to search for the alternate green energy sources. Natural sources like sun, wind, biological process, waves etc., have become viable alternatives for power generation. Wind energy has remained a popular source among them due to its commercial viability, and the net power production in this sector has undergone a steady growth in the recent past.

The power production and efficiency of a wind farm are mostly influenced by the forces acting on the turbines, which vary considerably over different geographical regions. In this context, wind turbines are of two types depending upon their location, i.e. onshore and offshore. Onshore wind turbines are easily accessible than offshore turbines and can be readily connected directly to local power grids. The wind speed in the onshore environment generally fluctuates due to various reasons, including its geographical features. Therefore, detailed analysis (i.e. micro-siting) is necessary to select the wind farm location to ensure availability of wind throughout the year, less impact on human settlement and nearby environment. Offshore turbines, on the other hand, are more profitable in the long run compare to its onshore version due to various factors (e.g. steady flow of wind over the years, availability of vast space for large wind farms, less noise pollution to the nearby settlements). Nevertheless, the construction, installation, and grid connection cost depends on the depth of water and site distance from the shore. However, the steady and higher wind speed in the marine environment has made offshore turbines commercially attractive, with 50% more power generation than an onshore turbine of similar size. Although they produce more power, they are exposed to a severe environment that demands a stringent design requirement for safe and sustained operation. The turbines in marine environment experience significant structural vibrations due to the combined effects of wind and wave.

The power produced by a wind turbine is proportional to its rotor area. Thus, modern megawatt turbines have a larger rotor diameter with flexible blades that undergo significant vibration when exposed to aerodynamic loads. Due to this reason, blades suffer fatigue and need regular maintenance. Besides fatigue and other associated issues, excessive deformation of the blade in the along-wind direction can lead to collision with the tower. In general, pre-cone angles are provided along with a tilted drivetrain to address this issue. However, pre-conning the rotor and tilting of the slow-moving shaft in the drivetrain develops additional stress on the gear tooth and root of the blade that ultimately induces damage and downtime for maintenance. The problem is more intense as the aerodynamic loads acting on the blades are cyclostationary in nature. Therefore, control and health monitoring are essential components to ensure safety during its operation to protect them against vibration-induced structural and mechanical damage.

For this purpose, researchers developed different vibration control strategies for wind turbines. Most of the vibration controllers are designed to operate in either flapwise or edgewise direction independently. This motivates to develop a controller that can reduce vibration in two orthogonal directions. A single controller that enhances the performance of a blade in both these directions without influencing the aerodynamics of the airfoils is indeed in demand. Thus, the present study proposes longitudinal stiffening of blades using a tendon made of shape memory alloy. The rationale behind selecting this smart material is due to its ability to offer excellent thermo-mechanical behaviour at low strain. A discrete reduced-order model considering the dominant modes of the tower, drivetrain and blade is developed with this stiffener for response analysis. It is based on using the distributed properties of tower and blade given for National Renewable Energy Laboratory (NREL) 5 MW benchmark turbine. The mode shapes are obtained from BModes, where the tower and blades are modelled as Euler-Bernoulli cantilever beams.

The three-dimensional wind field passing through the rotor plane is simulated using TurbSim package freely available from NREL. From this field, the aerodynamic loads are computed in MATLAB® using a modified version of Blade Element Momentum (BEM) theory. These aerodynamic loads are validated with widely used software AeroDyn. The wind turbines in the offshore environment are exposed to wave in addition to the aerodynamic loads. These wave loads are simulated using Morison's equation, where the wave time histories are generated from the Joint North Sea Wave Project (JONSWAP) spectrum considering two-dimensional wave propagation. The response of a benchmark wind turbine is simulated using these loads and validated with FAST. Further, this model is utilized to study the performance of the proposed control strategy. The non-linear material behaviour of the stiffener is modelled by combining the principles of thermodynamics with the constitutive models of SMA found in the literature (i.e. Liang-Rogers model). Thus, the super-elastic effects are utilized in semi-active mode (i.e. using Joule heating with the current flow) to apply actuation force that opposes blade deformation. An efficient switching algorithm is developed along with performance curves that enable the designer to select an optimal heating mode depending upon the operational scenario.

The numerical results presented in this thesis established the fact that different performance parameters (i.e. peak, peak-to-peak, mean, rms deformation of blade) are significantly reduced by the proposed stiffening strategy. Therefore, the proposed longitudinal stiffening offers an efficient solution reducing the dependence on tilt and pre-cone angle. Thus, the blade reliability against excessive deformation and subsequent collision with the tower is improved. For this purpose, a level crossing problem in the light of cyclostationary blade response is carried out using Rice formula, where the failure is modelled as a Poisson process. Sensitivity analysis is carried out to demonstrate the performance envelop of the proposed control strategy over the operational range of the benchmark 5 MW wind turbine for different diameter of the tendon.

Further, the impact of proposed stiffening strategy on fatigue life of a blade is investigated. For this purpose, a detailed spinning finite element model of the blade is developed by considering gyroscopic and Coriolis effect with respect to a non-rotating reference frame, where the displacement fields are evaluated using Hermitian shape functions. Modal analysis of the stiffened blade is carried out using this spinning finite element model, which shows significant improvement of bending stiffness. The variation of natural frequencies of the stiffened blade within its operational window (i.e. cut-in to rated rpm) are also studied using the Campbell diagram.

The impact of the proposed longitudinal stiffener on the stress profile and fatigue life of the blade are studied to show its performance under different design load cases as per IEC 61400-3. The fatigue damages at various locations is estimated using Palmgren-Miner's linear summation utilizing the cycle count obtained from the rainflow algorithm and S-N curve of Glass Fiber Reinforced Plastic (GFRP) material. Goodman diagram is used for the mean correction of stress response to obtain the allowable number of cycles from the S-N curve. The fatigue life of the blade using short-term damage under rated wind speed is improved 2 times with passive stiffener while its semi-active version shows 3 times increase. A sensitivity analysis based on peak stress and fatigue life reduction for different diameters of the tendon is also presented. Usually, wind turbines are exposed to various aerodynamic loads during their design life depend upon the environmental conditions. Hence, a long-term fatigue analysis is also carried out under different design load cases. The fatigue life of the blade with passive stiffener is improved by 60% while its semi-active version shows an increase by 13 times. Further, the damage equivalent stresses are evaluated for each design load cases. Also, the impact of the proposed stiffener on the reliability of blade against fatigue damage is studied. The numerical results obtained from this analysis highlights the performance enhancement in terms of serviceability (i.e. deformation of blades) and design against longitudinal stress, fatigue life and reliability.