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Modal Behaviour of Vertical Axis Wind Turbine Comprising Prestressed Rotor Blades: A Finite Element Analysis

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ABSTRACT

Pre-stressing is a concept used in many engineering structures. In this study prestressing in the form of axial compression stress is proposed in the blade structure of H-Darrieus wind turbine. The study draws a structural comparison between reference and prestressed configurations of turbine rotor with respect to their dynamic vibrational response. Rotordynamics calculations provided by ANSYS Mechanical is used to investigate the effects of turbine rotation on the dynamic response of the system. Rotation speed ranging between 0 to 150 rad/s was examined to cover the whole operating range of commercial instances. The modal analysis ends up with first six mode shapes of both rotor configurations. As a result, the displacement of the proposed configurations reduced effectively. Apparent variations in Campbell diagrams of both cases indicate that prestressed configuration has its resonant frequencies far away from turbine operation speeds and thus remarkably higher safety factor against whirling and probable following failures.

Keywords: Finite element analysis, H-Darrieus blade, prestressed blade, modal analysis, rotor dynamics, vertical axis wind turbine

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INTRODUCTION

The increasing demand for renewable energy, particularly wind energy, has seen the development of different types of wind turbines (Torabi Asr, 2016; Torabi Asr, Zal, Mustapha, & Wiriadidjaja, 2016). One of two ordinary types of wind turbines is the vertical axis wind turbine, shortly VAWT.

Darrieus turbines in their various forms, namely troposkien shape and H-shape, are the most conventional types of VAWTs (Paraschivoiu, 2002; Sutherland, Berg & Ashwill, 2012; Brusca, Lanzafame & Messina, 2014). VAWTs and specifically H-Darrieus-type rotors are easy to fabricate, easy to maintain and produce less noise than other conventional propeller-type turbines (Pathade, Pandhare, Saskar, Chaudhari, & Bairagi, 2016). More importantly, they can function independently of wind direction and thus do not require complicated yawing systems (Torabi, Osloob, & Mustapha, 2016; Al-Maaitah, 1993). Besides the advantages these class of wind turbines offer, their structure is exposed to large variation in torque with each revolution (Roy & Mohiuddin, 2015).

This study provides a pioneering approach in the load-bearing optimization of the turbine rotor by introducing prestress on the rotor blades. It suggests prestressed structure improves the integrity, stability and structure behavior. The aim of this paper is to draw a comparison of the dynamic behavior between the turbine rotors with prestress-reinforced blades and the original design.

METHODS

Finite Element Analysis

A conventional type H-Darrieus turbine rotor was modelled employing commercial finite element software ANSYS for conducting a modal analysis. As shown in Figure 1 the rotor comprising of three blades and a radial arm connecting the blades to the central column which is mounted on a supporting rigid part which acts as the bearing. Blades were of the so-called NACA 0018 airfoil in length. More detailed description of turbine rotor can be found in Table 1.

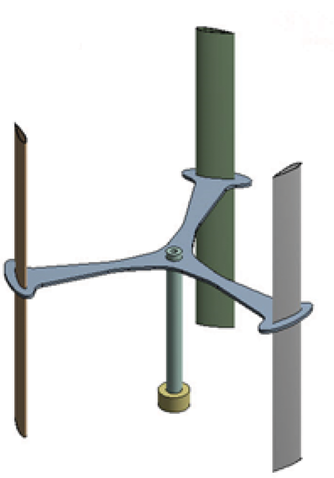

Figure 1. Test bed turbine model

Table 1
Test Bed Turbine Specifications

Quantity	Magnitude
Blade chord length	100 mm
Blade profile thickness	2.5 mm
Blade length	1000 mm
Rotor radius	400 mm
Radial arm thickness	10 mm
Blade mass	0.3 kg
Total rotor mass	3.2 kg

Aluminium alloy material which properties are shown in Table 2 was assigned to all parts excluding the supporting part which selected as a rigid body.

For the simulations conducted in this work, Hex Dominant method was used for the purpose of grid generation. A final mesh with approximately 34,000 elements was verified after conducting a grid study. Mesh cells start at 3 mm on blade edges and the maximum length of mesh cells did not to exceed 10 mm.

Table 2
Material properties (aluminium alloy)

Quantity	Magnitude
Young's modulus	71 GPa
Tensile yield strength	460 MPa
Shear modulus	26.7
Poisson's ratio	0.33

Simulations performed in this work can be categorized into two groups, namely reference and prestressed configurations. The latter group proposed a design in which turbine blades are initially reinforced by axial compression prestress of 10 MPa along their length. The choice of 10 MPa was selected after a preliminary study of several values ranging 5-15 MPa to provide an illustrative comparison between reference and prestressed configurations.

In order to juxtapose the structural dynamic behavior of these two configurations modal analysis, structure vibration responses, natural frequencies, and corresponding mode shapes were calculated. Of particular importance, due to the rotary operation of turbines, these structures are highly suspected to face resonance effect which can lead to whirling in some specific operational speeds and likely hazardous failures. Rotordynamics calculations provided by ANSYS Mechanical was used, and 25 rad/s-interval of rotation speed ranging between 0 to 150 rad/s were examined.

RESULTS AND DISCUSSIONS

Modal analysis has been performed on the turbine structure both for the reference configuration and the proposed prestressed. Figure 2 demonstrates the mode shapes for the reference configuration in the parked condition. As expected the rotor experienced considerable deformation, with a maximum displacement value of about 48 mm in the fourth mode shape.

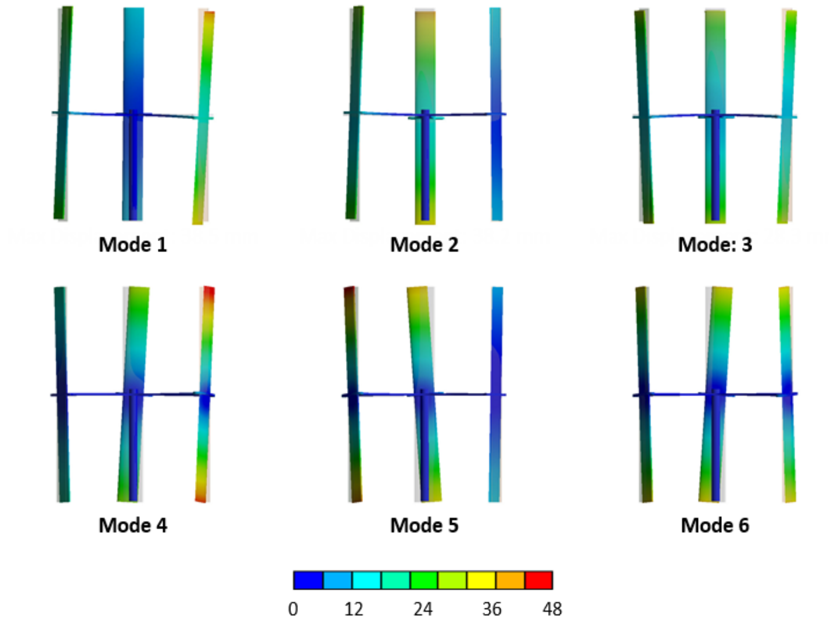

Figure 2. First six mode shapes for reference configuration coloured by total displacement [mm] representing variation from initial

More detailed information on the vibrational behavior of these two configurations is shown in Figure 3. It indicates employing the prestressed blades can offer an overall decrease in deformation amplitude at nearly all rotation speeds. In this respect, an average reduction factor of 20% was calculated for the maximum displacement.

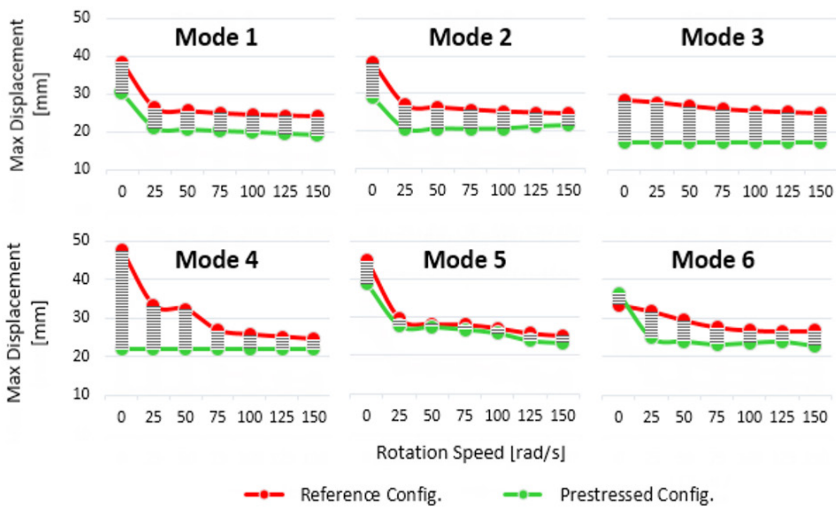

Figure 3. Maximum displacement occurred on turbine rotor over different rotation speeds at first six mode shapes

Based on the simulation results, increased rotation speed in turn, results in relatively less deformation once natural frequencies are expected to occur; however, the risk of resonance phenomenon can still be a concern. Regarding this issue, Campbell diagrams were plotted for both cases showing how the frequency of the different modes varies with the turbine rotation speed (see Figure 4). Intersection points where the Ratio=1 line crosses the curves considered as critical speed, in which rotor operational frequency comes in context with natural frequencies of turbine structure, the resonance phenomenon occurs and the response of the rotor shows a peak. In rotor dynamics, this is called as whirling and more specifically synchronous whirl, where the frequency of whirling is the same as the rotation speed.

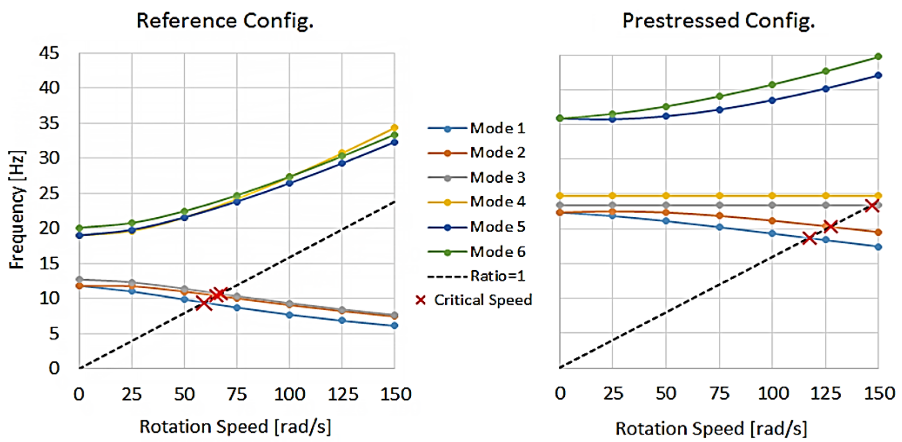

Figure 4. Campbell diagram for reference and prestressed configurations

Comparing these two Campbell diagrams, a considerable rise in natural frequencies or resonant frequencies can be seen for all speeds in prestressed blades. Moreover, the critical speeds from the original configuration ranging between 60 and 67 rad/s, corresponding to the first three mode shapes, shifted up significantly in the proposed design. A two-fold variation of lowest critical speed about 117 rad/s was observed which is fairly away from the normal operating condition of the commercial H-Darrieus turbines. The improved design contributes to greater protection from whirling and probable following failures. This is, in fact, in line with apparent growth in resonant frequencies of the structure due to the application of prestress-reinforced blades.

CONCLUSIONS

Results from the modal analysis show that applying a certain amount of axial pre-stress on turbine blades can significantly affect the dynamic response of the turbine structure. A one-fifth less average of maximum deformation which rotor structure is prone to while facing its resonant frequencies, as well as a wider whirling-free operational zone for the turbine with respect to its rotation speed (approximately up to 120 rad/s) are the advantages of employing prestress-reinforced blades. Prestressing can also be applied to all sizes and categories of Darrieus turbines.

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