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FEASIBILITY STUDY ON A NOVEL ACTIVE CONTROL CONCEPT FOR VERTICAL AXIS WIND TURBINE BLADES VIBRATION ATTENUATION INVOLVING BLADE MORPHING

FRED NITZSCHE [1] AND ALI SIAMI [2]

Department of Mechanical and Aerospace Engineering
Carleton University, Ottawa, Canada
e-mail: fred.nitzsche@carleton.ca

Abstract. Darrieus in 1931 patented a vertical axis wind turbine having two or more blades that follow the "troposkien" geometry, associated with a spinning rope shape, which is known to reduce the overall stress on the blades by reducing its transversal stresses. During the years following the first oil crisis in the 70's, the Darrieus received great attention from the industry. Extensive wind farms with this type of turbine were deployed However, the Darrieus design was subsequently abandoned due to unsolved problems associated with blade-vortex interactions on the blades that induced high vibration levels and, consequently, fatigue problems. In this paper, the feasibility of a novel control concept that involves blade morphing and do not demand extra actuators build with this purpose is investigated.

Keywords. Morphing, vertical axis wind turbine blades, Darrieus rotor, active control, vibration reduction, higher harmonic control

[1] Emeritus Professor
[2] Post-doctoral Fellow

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1. INTRODUCTION

There are two main types of wind turbines: horizontal axis (HAWTs) and the vertical axis (VAWTs). In terms of overall performance VAWTs are equivalent to HAWTs. Although HAWTs are well studied, VAWTs have received less attention throughout the years, because HAWTs inherited the well-established knowledge of propeller design. Another issue is the need of a starting torque mechanism to place the turbine into rotation. George Darrieus in 1931 invented and patented a VAWT having two or more blades resembling an eggbeater that follows a “troposkien” geometry associated, as the word translates from Greek, with the shape that a rope takes when it rotates about its extremities. [1] Because the rope is subjected only to axial stress, this geometry theoretically eliminates the transversal stress components acting on the blades. [2] However, as real blades have finite stiffness, even if very flexible they present residual transversal stresses in the practical implementations of the “troposkien”. [3] In special, at off-design rotating speeds substantially high transversal stresses are developed. [4, 5, 6]

During the years following the first oil crisis in the 70’s, the Darrieus VAWT received great attention from the industry. Extensive wind farms with this type of turbine were deployed in the Mohave desert (USA). In Canada, in the Gaspe Peninsula, the largest ever Darrieus VAWT prototype (4MW in power, 110m tall) was designed, [7] built, and became operational in the early 80’s. Regrettably, the Darrieus design concept was subsequently abandoned due to problems associated with blade-vortex interactions on the blades that induce excessive cyclic vibration levels (forced aeroelastic response phenomenon) precisely in the transversal direction of the blades and, consequently, catastrophic structural fatigue-related failures. [8]

For wind power harvesting in deep waters, the turbines are placed on offshore floating structures. The Darrieus VAWT become once more attractive when compared to competitive HAWTs designs because its center of gravity is inherently lower and closer to the see level and, thereof, the unit becomes dynamically more stable (see Figure 1). A European Framework Project was established to demonstrate a floating Darrieus concept, shown on the right end side of the figure. [9, 10] However, the early difficulties with the blades high vibration levels persist. Some aerodynamic flow control techniques can be copied from the already developed for HAWTs such as flaps used to alleviate structural loads at high winds. Nonetheless, their implementation in the Darrieus rotors is mechanically cumbersome due to their curved, flexible blade characteristics. Embedding “smart” morphing actuators in the blades would require too high actuation power and it is clearly prevented by the prerequisite of costs, simplicity, and reliability of the device in the field.

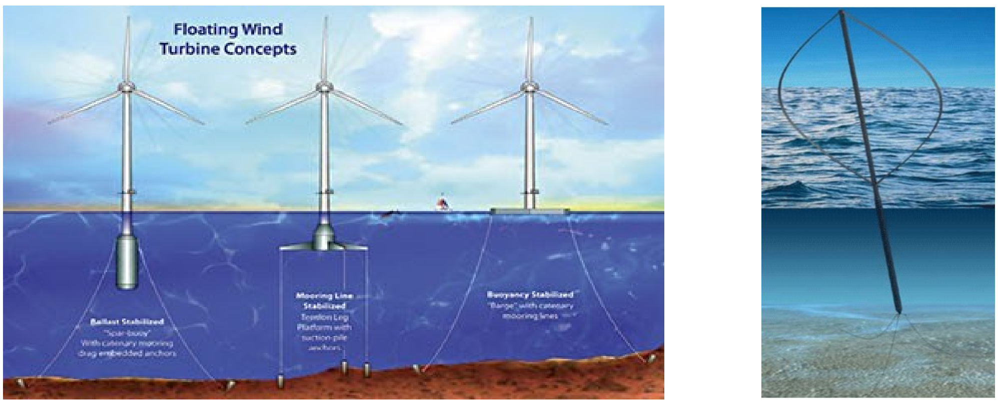

Figure 1: Different concepts for modern floating wind turbines. Horizontal Axis Wind Turbines (left), Darrieus Vertical Axis Wind Turbine (right) [9].

In this paper, an initial study on a novel control concept that also involves blade morphing but do not demand further embedded actuators will be investigated for its feasibility.

2. THE PROPOSED VIBRATION CONTROL CONCEPT

Inspired by the original idea developed at DTU for a floating Darrieus, [9] an actuation concept is proposed in this paper using instead of one submerged electrical generator, as suggested on the right of Figure 1, two submerged electrical generators that are independently connected by concentric axes to the ends of the blades. In Figure 2, the upper end of the blades is connected to the inner shaft and the lower end to the outer shaft. However, this arrangement is arbitrary; only the separation between the generators connect at the ends of the two blades is fundamental to the control concept. The idea of this actuation is to reproduce in the Darrieus the solution successfully achieved for the vibration problem of helicopters in forward flight, where a cyclic aerodynamic excitation (blade-vortex interaction) is also present. A technique called higher-harmonic control (HHC) – see for example [11, 12] will be employed, where the dynamic response of the helicopter blade can be tailored in the frequency domain by applying a pitch at the root of the rotorblade. In the latter case, the control input twist is commanded by the swashplate using a relatively small amplitude periodic signal and produces higher-harmonic aerodynamic loads by changing their angle of attack. These superimposed dynamic loads shall counteract the uncontrolled dynamic response of the blade at the harmonics of the rotor fundamental frequency (i.e., the rotor angular velocity). As opposed to helicopters (or HAWTs), the Darrieus blades are fixed (cantilevered or pinned) at the two ends; therefore, the desired twist action will be commanded by the phase between the two generators, which is forced into a small amplitude HHC input motion. Hence, in the proposed scheme, *the actuation twist rather than use embedded smart materials or moving flaps will be produced by a commanded differential phase angle (periodic) imposed by the two generators at the two extremes of the blades throughout their rotation*. Following the HHC technique, one generator will rotate at the rotor fundamental frequency, Ω_0 and the other at $\Omega_0 + \Omega(t)$, where $\Omega(t) = n\Omega_0 \pm \varphi(t),$ n being an integer. Both the phase between the two generators, given by $\pm\varphi(t)$, and the frequency multiple of the fundamental will be introduced by an electrical auxiliary circuit fed by the energy harvested itself. As seen, *there is no need of to introduce extra actuators because the control scheme uses the generators alone for this purpose*, which, by design, shall be strong enough to generate the differential torque applied on the extremities of the blades. An evaluation of this actuation concept versus the twist imposed on the blades by the HHC is the object of the present paper.

In the Darrieus rotor, the vibrational modes are coupled by the Coriolis effect. [6, 13] As a result, the twist and transversal operational modes of vibration are highly coupled by the aerodynamic loads, which, near their resonance frequencies, can produce adverse effects to the control scheme. Hence, the results of the present feasibility study should be taken cautiously and may not be considered complete without a further comprehensive aero-servo-elastic analysis and improvement of the control algorithm.

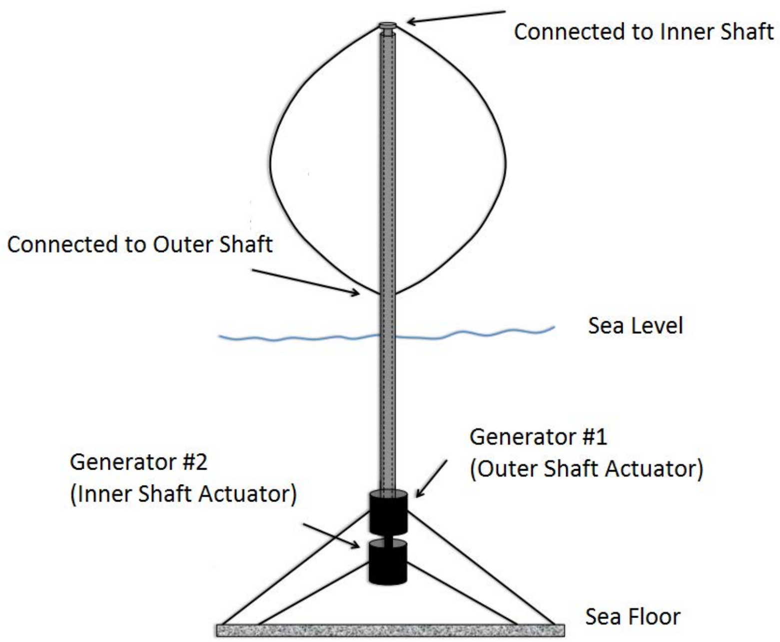

Figure 2: Novel blades morphing actuation concept investigated in this work.

3. NUMERICAL SIMULATIONS

A one-dimensional (1D) nonlinear blade model based on Hodges' formulation [14] is employed to identify the required active control under specified harmonic external loads. A slender curved blade with NACA0012 airfoil is used in this study, with the properties seen in Table 1. The cross-section of the blade using 1032 linear quadrilateral finite elements is plotted in Figure 3. This grid is used into a cross-sectional analysis package developed by the authors to calculate the structural properties required for the subsequent 1D analysis. The results have been verified using both the commercial packages VABS for the cross-section analysis and a detailed three-dimensional (3D) model of the blade developed in ANSYS for the 1D reduced-order model calculations. More details can be found in former papers. [16, 17, 18]

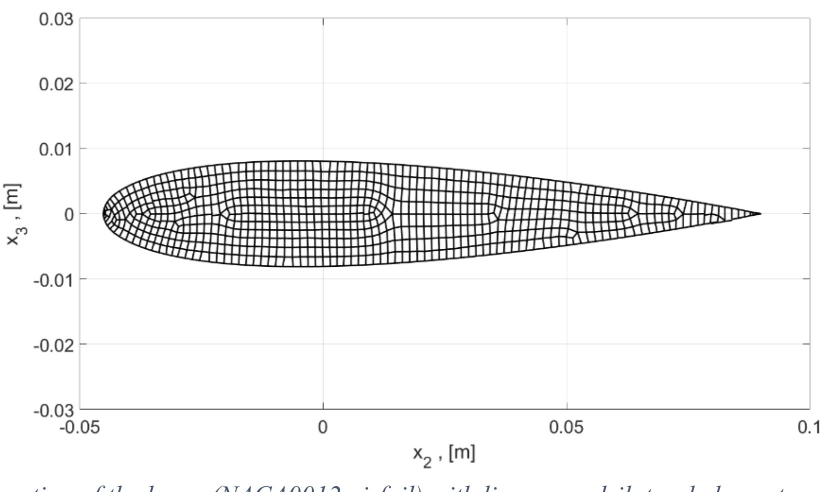

Figure 3: Cross-section of the beam (NACA0012 airfoil) with linear quadrilateral elements used for the cross-sectional analysis.

Table 1. Properties of the troposkien-curved blade.

Geometrical properties	
Airfoil	NACA0012
Chord length	$0.135\ [m]$
Length of blade	$1.5\ [m]$
Material properties	
Young's Modulus (E)	$7.1 \times 10^{10}\ [Pa]$
Shear Modulus (G)	$2.6692 \times 10^{10}\ [Pa]$
Poisson's ratio (ν)	0.33
Density (ρ)	$2770\ [kg/m^3]$
Boundary condition and rotational speed	
At the lower end ($x_1 = 0$)	clamped
At the upper end ($x_1 = L$)	pinned
Rotational speed of wind turbine (Ω_0)	$2.5\ [rad/s]$

The 1D model of the blade with the applied boundary conditions is shown in Figure 4. As can be seen from this figure, at the lower end the clamped boundary condition is applied, whereas at the top end the pinned joint was considered. In Figure 4, the inertial frame is denoted by (x, y, z). The undeformed state of curved blade is expressed in the local b coordinates, defined along the b_1 (chordwise), b_2 (edgewise) and b_3 (flapwise) directions. [16]

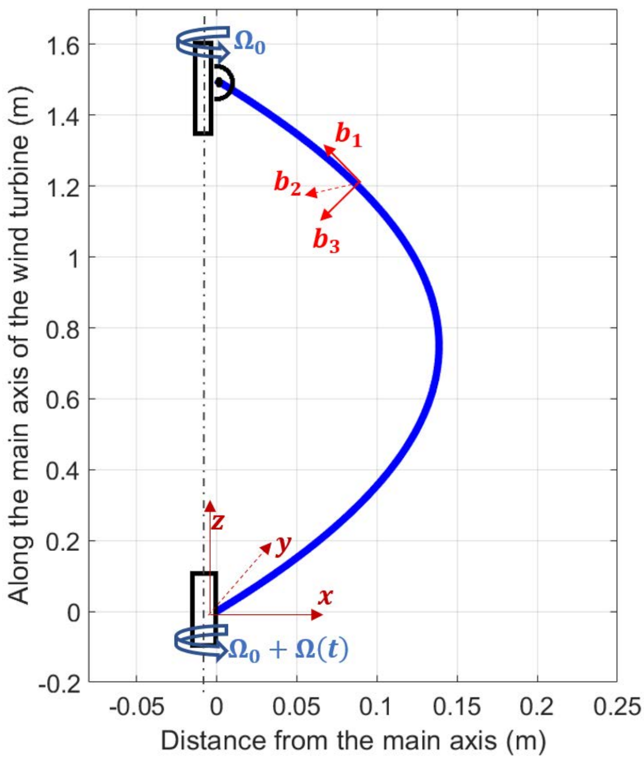

Figure 4: The 1D model of the blade with the applied boundary conditions.

The external forces applied on the blade are presented in Figure 5. As seen, they are considered both harmonic along the flapwise and edgewise directions to simulate the aerodynamic lift and drag. The forces are, however, assumed uniformly distributed along the span. Although these force distributions are obviously not representative of the actual aerodynamic lift and drag, their magnitudes in this study respectively match their maximum amplitudes at the equator of a turbine of this size. This simplification is granted because only the blade morphing capability under the higher harmonic (HHC) excitation imposed at one end is being questioned in this first feasibility study. As such, at the clamped end of the blade ($x_1 = 0$), a time-variant rotational speed with a higher harmonic time history is applied along the *z*-axis.

Galerkin's approach combined with a time-marching method is used here to solve the intrinsic 1D nonlinear equations of the troposkien-curved blade. [18] The results of the numerical simulations performed are presented next.

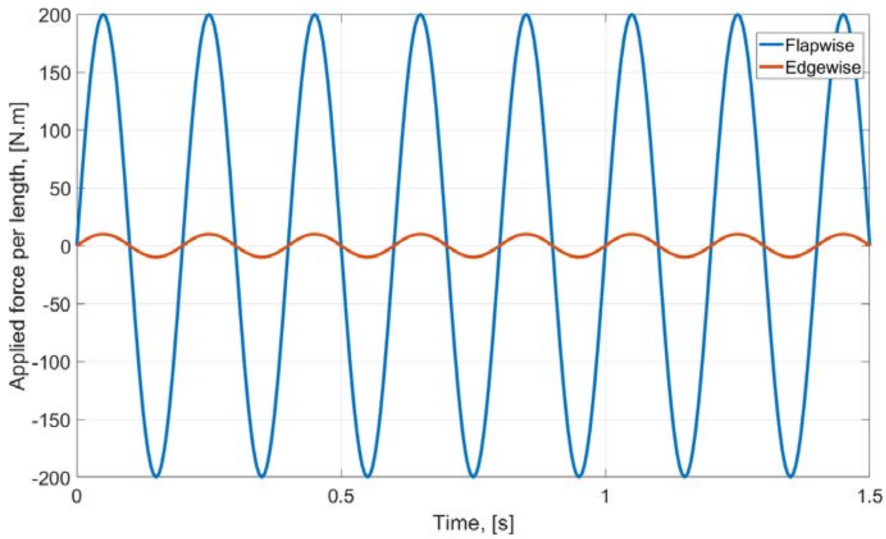

Figure 5: External harmonic forces uniformly applied along blade span in the two orthogonal directions (flatwise in blue and edgewise in red).

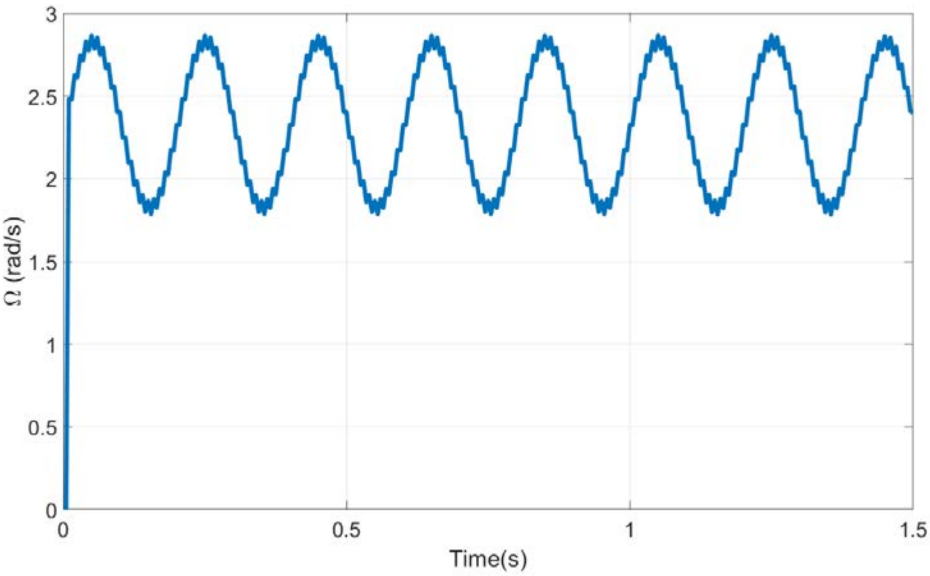

Figure 6: Simulated time-variant boundary condition (rotational speed in z-direction) at the root of the blade.

The calculated rotational speed in the z-direction at the root of blade is shown in Figure 6. It is clear from this figure that at the lower end of the blade the solution converges to the imposed higher-harmonic boundary condition. Both the constant and the time-variant parts of the rotational speed have been captured using the solution method. The moment in the z-direction that was obtained from the simulations at the lower end of the blade and must be identified to the torque supplied by the generator under HHC is plotted in Figure 7.

As it must be expected from the applied boundary conditions, the calculated moment at the upper, pinned end of blade ($x_1 = 1.5\ m$) is almost equal to zero, as verified in Figure 8.

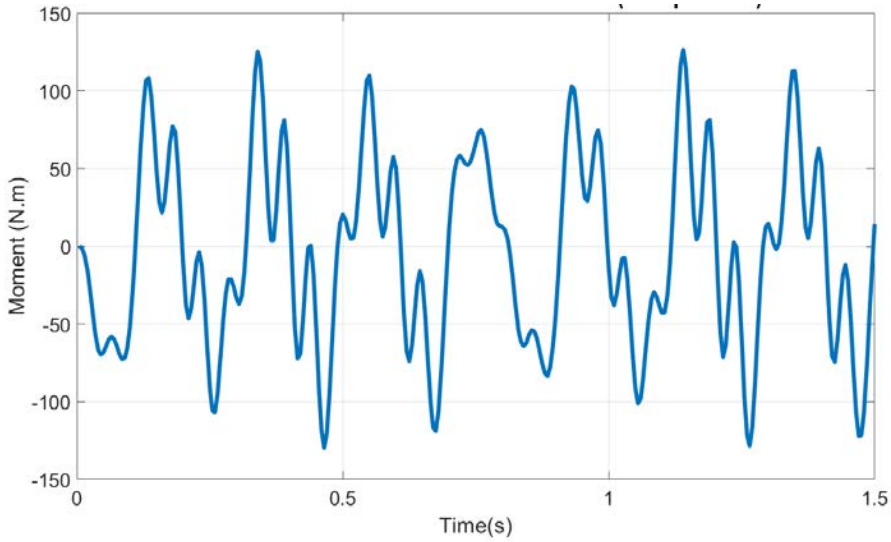

Figure 7: Calculated moment in the z-direction at the lower end of the blade

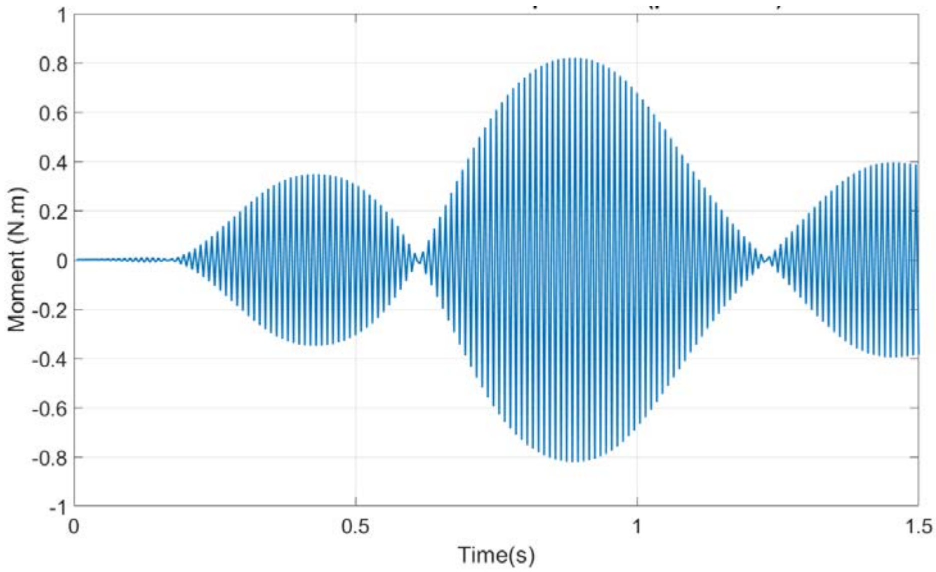

Figure 8: Calculated moment in the z-direction at the upper end of the blade.

4. ANALYSIS OF SIMULATION RESULTS

The linear displacements of the blade under the action of all harmonic loads in the direction normal to the main axis of the wind turbine are plotted in Figure 9 at the different time steps considered in this analysis. This figure not only confirms that the prescribed boundary conditions have been satisfied at the two ends of the blade but also that the proposed HHC action is producing significant displacements. The corresponding rotation angles around the *z*-axis at these time steps are presented in Figure 10. Most importantly, the latter figure indicates that a maximum of 0.04 rad (or 2.3 degrees) of rotation are achieved at the upper end of the blade when the harmonic control input is applied at its lower end. As this rotation is directly identified to the angle of attack produced by HHC, the feasibility of the proposed control scheme is demonstrated. This conclusion is also supported considering the relatively low reaction torque that must be supplied by the generator at the lower end of the blade to perform HHC, as depicted in Figure 7 (i.e., approximately 100 N.m in magnitude).

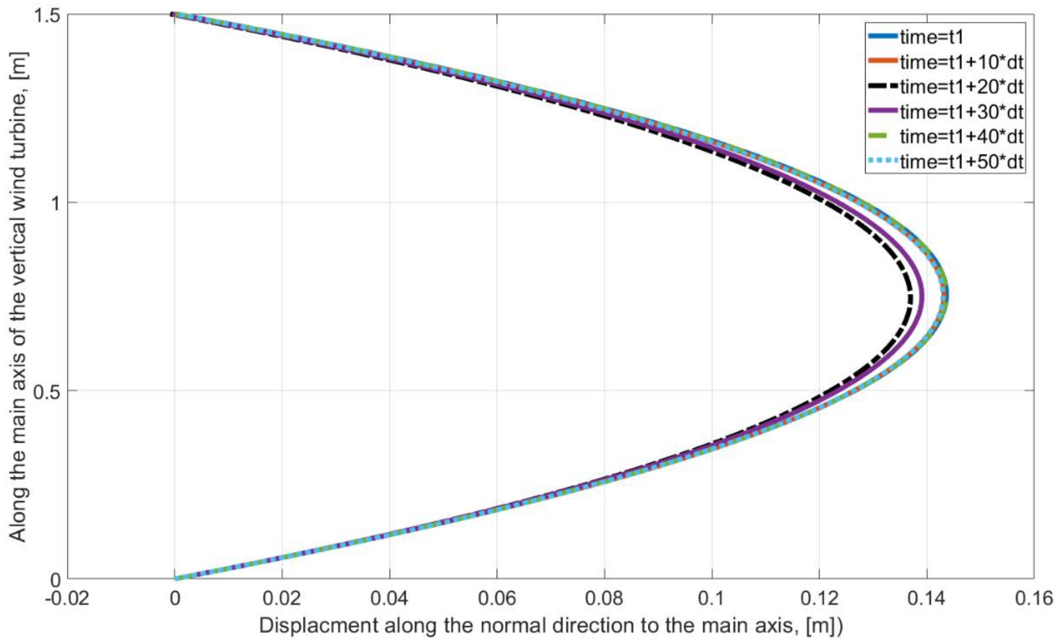

Figure 9: Obtained displacement along the blade span under the applied external forces at the considered time steps.

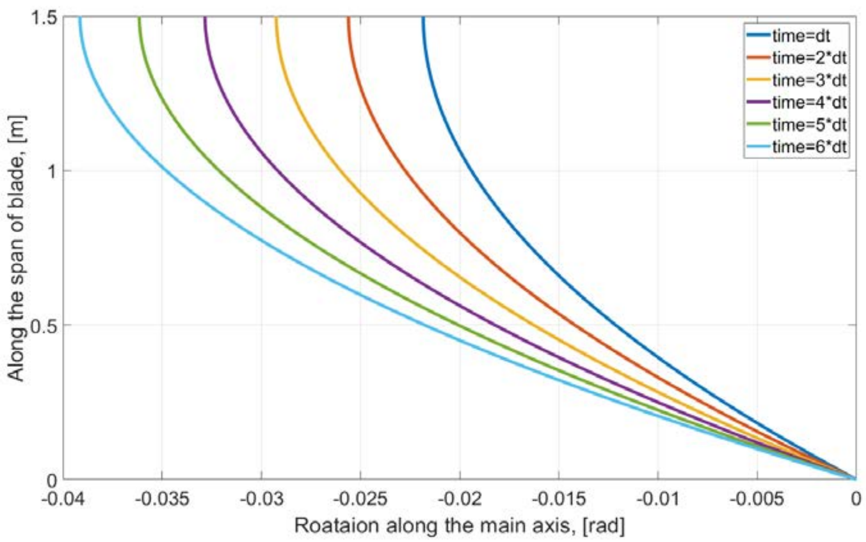

Figure 10: Calculated rotation along the z-axis at the root at the considered time steps.

However, as previously mentioned, no aeroelastic simulations have been completed in the present study to fully qualify the control strategy. Furthermore, the control strategy must be refined and tailored using an aero-servo-elastic approach. One of the obvious improvements would be to explore the ability that the proposed strategy brings to control both ends of the blades using different out-of-phase HHC inputs on the two generators located at the upper and lower ends, respectively. In this case, the phase difference between the two HHC inputs, denoted by $\pm\varphi(t)$ in Section 3, would play a fundamental role. With this ability, the location of the point of the maximum generated angle of attack depicted in Figure 10 could be moved to be not at the upper end but towards to the equator of the turbine, where the most adverse blade-vortex interaction effects are verified. In this case, not only vibration control could be achieved, but also the turbine power coefficient could be maximized as suggested in another publication. [19, 20]

5. CONCLUSIONS

The present study explored a novel morphing control scheme that is proposed to attenuate adverse blade-vortex interactions of the Darrius-type vertical axis wind turbines. The first study indicates that the higher-harmonic control (HHC) strategy using the turbine electric energy generators themselves instead of dedicated actuators is feasible when only the most fundamenal metrics of generated angles of attack versus required input torque are employed. This control technique can be utilized to promote the usage of these turbines with less practical problems associated with the structural fatigue that is induced by the high levels of vibrations verified in the field.

Lastely, the numerical simulations based on Galerkin's approach for solving the 1D nonlinear equations developed by the authors in previous papers showed to provide a powerful computational tool for evaluation of non-linear active control strategies when applied to blades with substantial intitial twists and curvatures.

REFERENCES

1. Darrieus, G. Turbine Having Its Rotating Shaft Transverse to the Flow of the Current. U.S. Patent 1835018, December 1931.
2. Blackwell, B.F., and Reis, G.E., Blade Shape for a Troposkien Type of Vertical-Axis Wind Turbine, Sandia National Laboratories Report SLA 74-0154, NM (USA), April 1974.
3. Reis, G.E., and Blackwell, B.F., Practical Approximations to a Troposkien by Straight-Line and Circular-Arc Segments, Sandia National Laboratories Report SAND 74-0100, NM (USA), March 1975.
4. Lobitz, D.W.,VAWT Rotor Structural Dynamics analysis methods. In *Proceedings of the Vertical Axis Wind Turbine (VAWT) Design Technology Seminar for Industry*, pp. 156–175, Albuquerque, New Mexico, April 1980.
5. Lobitz, D.W. and Sullivan, W.N., Comparison of finite element predictions and experimental data for the forced response of the DOE 100 kW vertical axis wind turbine. Technical report, Sandia National Labs., Albuquerque, NM (USA), 1984.

6. Fereidooni, A., Numerical Study of Aeroelastic Behaviour of a Troposkien Shape Vertical Axis Wind Turbine. Master of Applied Sciences thesis, Department of Mechanical and Aerospace Engineering, Carleton University, Ottawa, Canada, 2013.
7. Templin, R.J., Aerodynamic performance theory for the NRC vertical axis wind turbine, NRC of Canada. Technical report, LTR-LA-160, 1974.
8. Kumar, P. et al., "Review on the Evolution of Darrieus Vertical Axis Wind Turbine: Large Wind Turbines," *Clean Technol*., 2019, 1, pp. 205–223; doi:10.3390/cleantechnol1010014
9. Vita, L., Paulsen, U.S., Padersen, T.F., Madsen, H.A., Rasmussen, F., "A Novel Floating Offshore Wind Turbine Concept," PO 276, European Wind Energy Conference and Exhibition, Marseille, France, 2009.
10. Paulsen, U.S., et al., *DeepWind Project*, 7th European Framework Program (FP7), 2010-2014.
11. Reichert, G., "Helicopter Vibration Control – A Survey." In *Proceedings of the Sixth European Rotorcraft and Powered-Lift Aircraft Forum,* September 1980.
12. Loewy, R.G., "Helicopter Vibrations: A Technological Perspective," *J. American Helicopter Society,* Vol. 29, No. 4, October 1984, pp. 4-30.
13. Nitzsche, F., Aeroelastic analysis of a Darrieus type wind turbine blade with troposkien geometry. PhD thesis, Department of Aerospace Engineering, Stanford University, Palo Alto, California, USA, 1983.
14. Hodges, D.H., "A mixed variational formulation based on exact intrinsic equations for dynamics of moving beams," *International Journal of Solids and Structures*, 26 (1990), pp. 1253–1273.
15. Cesnik, C.E.S., Hodges, D.H., "VABS: a new concept for composite Rotor blade cross-sectional Modeling," *Journal of the American Helicopter Society*, 42 (1997), pp. 27-38.
16. Siami, A. and Nitzsche, F., "A semi-analytical approach for the variational asymptotic sectional analysis of a beam with high values of initial twist and curvatures," *Journal of Mechanics of Materials and Structures,* 2023 (accepted; in publication stage).
17. Siami A., and Nitzsche F., "A harmonic balance solution for the intrinsic 1D nonlinear equations of the beams," *Journal of Vibration and Control,* 2023 (doi:10.1177/10775463231162751).
18. Siami A., Nitzsche F., Leibbrandt R., et al., "Dynamic response analysis of the helicopter blades with non-uniform structural properties," *AIAA SciTech Forum* 2021 (doi.org/10.2514/6.2021-0562).
19. Hilewit, D., Matida, E. A., Fereidooni, A., El-Ella, Hamza-Abo and Nitzsche, F., "Numerical investigations of a novel vertical axis wind turbine using Blade Element Theory - Vortex Filament Method (BET-VFM)," *Journal of Energy Science & Engineering*, 2019; 7:2498-2509 (doi.org/10.1002/ese3.438).
20. Hilewit, D., Matida, E. A., Fereidooni, A., El-Ella, Hamza-Abo and Nitzsche, F., "Power Coefficient Measurements of a Novel Vertical Axis Wind Turbine," *Journal of Energy Science & Engineering*, 2019; 7:2373-2382 (https://onlinelibrary.wiley.com/doi/full/10.1002/ese3.412).