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DeepWind'2013, 24-25 January, Trondheim, Norway

## Design Optimization of a 5 MW Floating Offshore Vertical-Axis Wind Turbine

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### Abstract

This paper outlines results of a proposed layout of a light 2-bladed rotor, with a driving torque constraint matching the generator design, and shows details of the pultruded blade – and rotor geometry. In comparison with the 1<sup>st</sup> baseline design of a 5 MW VAWT concept this present development provides during standstill and operation significant less mass with a comparable level of loading strain in the blades and in the junctions between blade and tower. Optimized blade profile having a low weight and high stiffness is obtained according to the design evaluations based on the standstill calculations in ANSYS software. The selected profiles are used in the aero dynamic simulation. Furthermore the simulation code will be demonstrated to show the fully development model, integrating the simulation of turbulent wind inflow, actuator cylinder flow model, power controls, hydraulic floater - and mooring line systems implementation.

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*Keywords:* vertical axis; structural design; pultrusion; floating offshore wind turbine; submerged generator; optimization

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## 1. Introduction

The DeepWind concept<sup>1</sup> as shown in Figure 1 (left view) has been presented as a new offshore wind turbine concept with cost reduction potentials. The 4-year European funded FP7 project explores until October 2014 on a Darrieus type of rotor with new materials and technologies in an offshore deep-sea environment. The concept has been investigated at the Hywind wind turbine site integrating a two-bladed Troposkien shaped vertical-axis wind turbine (VAWT) with a rotating spar platform. The simulation code has been developed on the basis of the aeroelastic code HAWC2[1] to include what is needed to calculate VAWTs in deep-sea conditions[2,3]<sup>23</sup>, to adopt for more adequate aerodynamic VAWT model<sup>45</sup>, and recently to implement the capability to model mooring lines, as shown in Figure 1(right view).

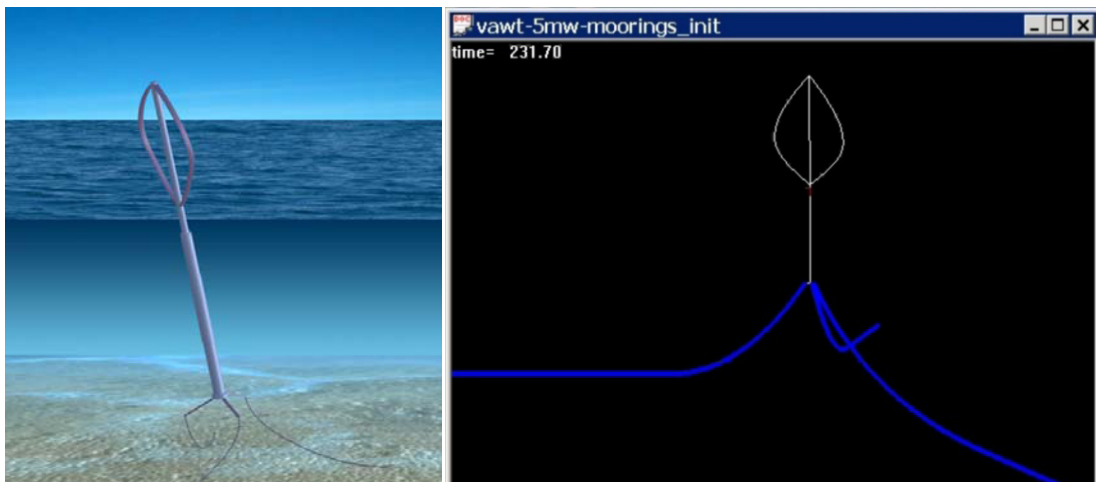


Figure 1 Left: Vertical-Axis Darrieus concept for deep sea. Right: A 5MW DeepWind turbine concept with mooring lines modelled in HAWC2. Rotor height is 130m and the rotating floater 107m long.

The definition of constraint design drivers (loads, stability, cost) [2] led to a 1<sup>st</sup> baseline design<sup>23</sup> [3, 4] with emphasis to achieve a rational torque absorption in loads reduction and balanced power controls on a given rotor shape and -blade design. The study showed in particular for rotor loading that rotor shape, blade design and operational conditions are sensitive for layout of the blade webs with consequences on the blade weight.

<sup>1</sup> Vita L, Paulsen US, Pedersen TF, Madsen HA, Rasmussen F *A Novel Floating Offshore Wind Turbine Concept*. Proceedings of the European Wind Energy Conference (EWEC), Marseille, France; 2009.

<sup>2</sup> Vita L, Paulsen US, Madsen HA, Nielsen PH, Berthelsen PA, Carstensen S *Design and aero-elastic simulation of a 5MW floating vertical axis wind turbine*. Proceedings of the ASME 2012 International Conference on Ocean, Offshore and Arctic Engineering OMAE 2012, Rio de Janeiro, Brazil; OMAE2012-83470; 7: p. 383-292

<sup>3</sup> Berthelsen, PA, Fylling I, Vita L, Paulsen US *Conceptual Design Of A Floating Support Structure And Mooring System For A Vertical Axis Wind Turbine* Proceedings of the ASME 2012 International Conference on Ocean, Offshore and Arctic Engineering OMAE 2012, Rio de Janeiro, Brazil; OMAE2012-83335; 7: p. 259-268

<sup>4</sup> Madsen HA, Larsen T, Paulsen US *Analysis of VAWT aerodynamics and design using the actuator cylinder flow model* Presentation at Torque 2012 Oldenburg. Available at <http://www.forwind.de/makingtorque/Program.html>

<sup>5</sup> Madsen HA, Larsen T, Paulsen US *Adoption of the aeroelastic code HAWC2 for vertical axis turbines using the actuator cylinder flow model* AIAA 51st Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition 07 - 10 January 2013, Grapevine (Dallas/Ft. Worth Region), Texas USA

In the survey a lower solidity as well as to consider a higher rated power was suggested as well. This improves the rotor stall characteristic and moves the rated conditions towards higher values of rotational speed and lower wind speed which results in a less costly generator. Another design option is to use a thinner airfoil which could improve the rotor stall characteristic. In order to take steps towards the realization of a lighter rotor than the 1<sup>st</sup> baseline 5 MW rotor, we have in this paper included the rotor design based on a lower solidity and slightly higher rpm. We describe how an optimization of the rotor blades are carried out under specific design constraints.

The recent developments for defining the full model contain an actuator cylinder flow model<sup>4</sup> and a revision for incorporation of turbulent wind<sup>5</sup>. The hydrodynamic interaction of waves and current has been investigated in a scale model experiment<sup>6</sup>, and an engineering model of the results is ready to be implemented in the code, but will not be demonstrated in this paper.

### 1.1. Wind Turbine Characteristics

The 1<sup>st</sup> baseline design shown in Table 1 resulted in blade weight of 154 tons for a turbine with a 7.45 m chord. It was realized, that such a design would have large negative impacts on the systems design. Therefore it was suggested that alternative blade designs such as using piecewise constant profiles, and thick profiles should be explored. This led to the consideration of combining the alternative designs with iteration in the system design.

Following the guidelines[3] on improving the 1<sup>st</sup> baseline 5 MW design, the 2<sup>nd</sup> iteration resulted in a new rotor design, namely: higher rated power (approximately 6200 kW,+24%), higher rpm at rated power (5.63 rpm,+7.0%), lower solidity (0.15,-32.9%); the maximum rotor radius is 60.49m (-5.1%), the rotor height is 143 m(+10.4%), the swept area 12318 m<sup>2</sup>(+14.7%) and the chord is 5 m(-32.9%).

The power curve is shown in Figure 2(left), together with the thrust curve(right). The power curve from this 2<sup>nd</sup> iteration loop has a distinct stall in the wind speed range of 14 -17 m/s. However, for higher wind speeds the power increases which likely gives a less easy aerodynamic damping during a complete rotation of the blades. This will be investigated more in detail.

Table 1 1<sup>st</sup> baseline 5 MW rotor design

Geometry			Performance		
Rotor radius (R)	[m]	63.74	Rated power	[kW]	5 10 <sup>3</sup>
Rotor height (H)	[m]	129.56	Rated rotational speed	[rpm]	5.26
Chord (c)	[m]	7.45	Rated wind speed	[m/s]	14
Solidity ( $\sigma = Nc/R$ )	[-]	0.23	Cut in wind speed	[m/s]	5
Swept Area	[m <sup>2</sup> ]	10743	Cut out wind speed	[m/s]	25

<sup>6</sup> Carstensen S, Mandviwalla X, Vita L, Paulsen US *Lift of a Rotating Circular Cylinder in Unsteady Flows* Proceedings of 22nd International Offshore and Polar Engineering Conference, Rhodes June 2012

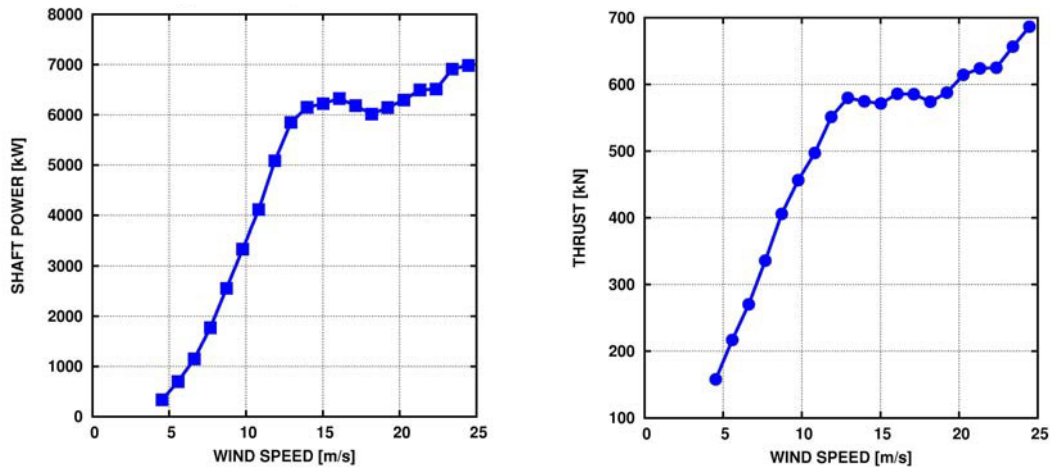


Figure 2 2<sup>nd</sup> iteration 5 MW rotor design. Left: Power vs wind speed. Right: Thrust vs wind speed

### 1.2. Optimization procedure

The 1<sup>st</sup> baseline design was found to inherit too high blade mass, which contributed to increased material costs. The constraints of the design discussed in [2, 3] include the platform and the sea conditions<sup>2</sup>. The exploration of the platform design has shown minor influence of the wind turbine mass and inertias, but likely more on the thrust and moments exerted on the platform. With this in mind it is assumed that we can carry out a more direct optimization of the rotor without considering floater interaction. The constraints (structural and cost) are here with this design expressed as load per blade, blade material cost per m as design drivers. The blade shape and the blade profiles in terms of material properties are given for a range of rotor speeds and given rotor height/rotor diameter variables. The NACA aerodynamic profile series with thickness 18%, 21% and 25% are selected as representatives of a class of advanced profiles worked on in the project. The procedure to optimize the rotor design on the blades is 1) to explore the 1<sup>st</sup> baseline design under standstill with the aim to reduce the weight and improve the distributed material properties expressed by a uniform profile with a constraint of less than 5000  $\mu$  m/m strain [7] and 2) with the same constraint but now with the sectioned blade properties along the blade arc to investigate the loads under rotation.

A static analysis of the rotor subjected to its own weight is carried out in the general purpose finite element (FE) software ANSYS [5]. The schematic of the standstill simulation is shown in Figure 3(left). The tips of the rotor are assumed to be fixed to the shaft. The rotor is modeled using quadratic 3D BEAM189 elements which have 3 nodes and include also the shear deformation effects. The BEAM189 element is well suited for large rotation and/or large strain nonlinear applications [5]. The aforementioned NACA profile series are used for the cross-section of the blade having a chord length of 5 m. A relatively simple cross section having 2-spars is considered in this study as compared with the one used in [3]. A representation of the blade for a NACA0018 profile is shown in Figure 3(right). Brief details of the cross section for the different profiles used in this work are given in Table 1. According to the design evaluations performed in ANSYS, an optimized blade having low weight and high stiffness is obtained leading to the maximum linear elastic strain being less than 5000  $\mu$  m/m. The selected profiles are used in HAWC2 and the “dynamic” performance of the rotor is simulated in terms of the normal force and the local flapwise moment during the specified rotation.

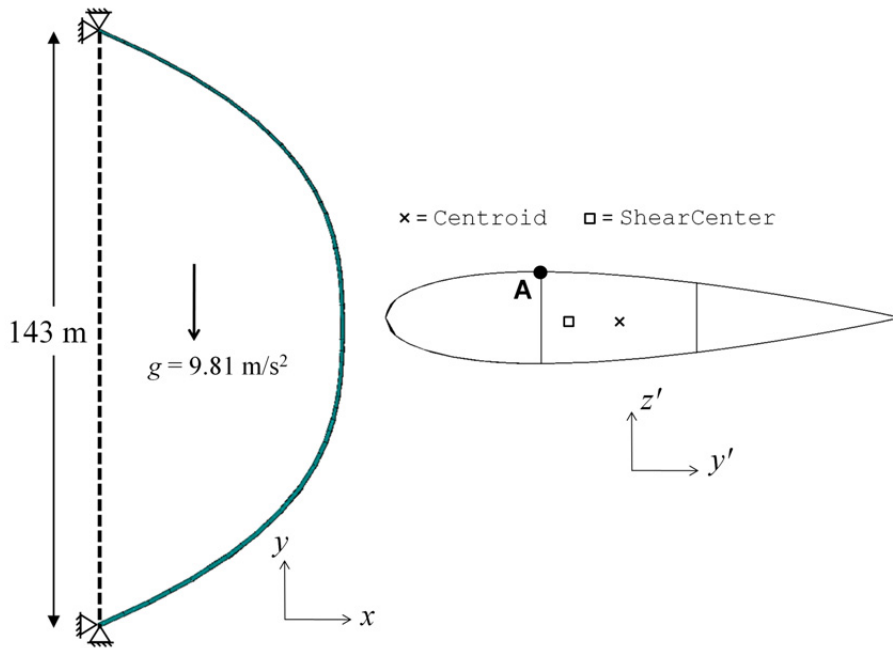


Figure 3 Left: Schematic of standstill simulation in which the rotor is subjected to its own weight. Right: Cross section of the NACA0018 profile having a chord length of 5 m.

Table 2 Cross section of NACA0018 profile having a chord length of 5 m.

		NACA0018	NACA0021	NACA0025
Cross sectional area	[m <sup>2</sup> ]	0.1217	0.1262	0.1323
Specific mass	[kg/m]	219.2	227.2	238.1
Area moment of inertia about the y' axis (Fig. 3)	[m <sup>4</sup> ]	0.0117	0.0163	0.0237
Area moment of inertia about the z' axis (Fig. 3)	[m <sup>4</sup> ]	0.2504	0.2607	0.2748

## 2. Results

### 2.1. Constant blade chord with same profile

In this section, a constant or uniform blade section is considered throughout the rotor. The displacement fields of the rotor from the standstill simulations are shown in Figure 4(left) for a blade thickness of 18%, 21% and 25%. It is seen that the smallest displacement field is obtained for uniform NACA0025 section throughout the rotor although it has the highest rotor weight of 47627 kg/blade and the highest stiffness of the three uniform blade profile sections. The corresponding longitudinal linear elastic strain distributions for point A (Figure 3) which is located at the inner side of the rotor are given in Figure 4(right). Since the NACA0018 section has the smallest weight (43812 kg) and stiffness, the calculated strain levels are relatively large for this profile. The stiffness and weight (45453 kg) for the NACA021 blade lies in between the other profile sections.

The tips of the rotor are fully constrained in all directions. Therefore, the maximum elastic strain occurs close to the tips. Apart from in the area of the tips, smaller strains, i.e. smaller than  $5000 \mu\text{m}/\text{m}$  strain are obtained. Therefore, the tips can be omitted for the evaluation of the maximum strain since these must somehow be strengthened by using some sort of metal hub attached to the shaft by e.g. bolts. This would of course increase the stiffness of the rotor at the tips which decreases the strain at the tips. The maximum strain values apart from the tips are obtained at the rotor heights of approximately 28 m and 110 m.

The loads subjected on the present rotor which has the above constant, but lesser blade chord and uniform profile NACA0018 are approximately 30% lesser than the 1<sup>st</sup> baseline design. The lesser flapwise loads are for thicker profiles transferred into less strain as the relative thinner airfoil as indicated in Figure 3, right.

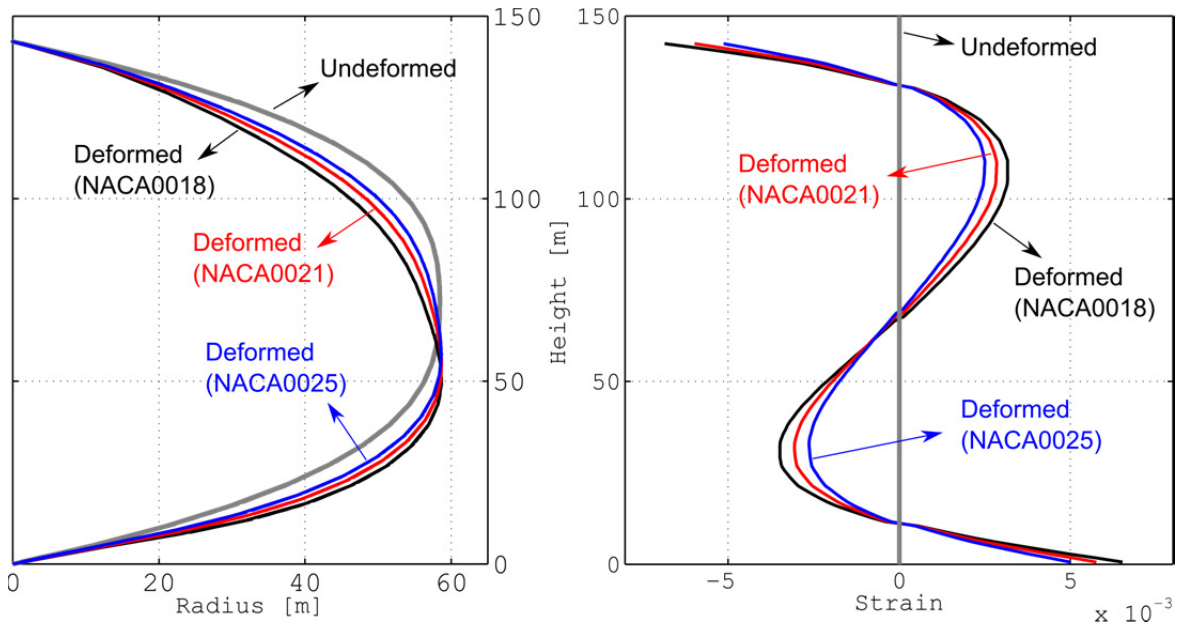


Figure 4 Left: ANSYS calculations of the deformation of the rotor having uniform blade cross sections, and right: corresponding strain distributions for the uniform rotor at point A (see Fig. 3) which is located at the inner side of the rotor.

## 2.2. Constant chord with different profile

The combinations of the aforementioned blade cross sections are considered in ANSYS for the sectionized rotor design in order to decrease the total weight. The schematic of the sectionized rotor is seen in Figure 5(left). The section locations are determined according to the strain distributions in Fig. 4 such that the maximum strain values apart from the tips are considered. Two different configurations of the rotor are analyzed and the details are given in Table 2. In Case-1, a thicker blade is used for the middle section as compared to the top section and the reverse is the case in Case-2. The calculated elastic strains in the longitudinal direction for point A (Figure 3) are shown in Figure 5(right). It is seen that a similar strain distribution is obtained for Case-2 as compared to the one obtained for the uniform rotor having the NACA0025 profile except at the middle section. It should be noted that the total weight of the sectionized rotor in Case-2 is lower than the uniform rotor having the NACA0025 profile which has the highest



stiffness. Using a thicker blade profile at the top (Case-2) decreases the strain values as compared to Case-1 in which a thicker profile is used at the middle. The corresponding total weights of the blades are given in Table 3. It is seen that the weight values for uniform and sectionized rotor are approximately close to each other.

Table 3 Details of the sectionized rotor.

	Section-1 (Bottom)	Section-2 (Middle)	Section-3 (Top)	Total blade weight (kg)
Case-1	NACA0025	NACA0021	NACA0018	45670
Case-2	NACA0025	NACA0018	NACA0021	45844

In Figure 6 the results from HAWC2 simulations are shown for the consequences of the loads during operation at 10 m/s and at standstill for Case-2. From Figure 6, left it is observed, that there is insignificant influence on the mean value from air loads, and some influence from the variation of the rotating blades per revolution. In comparison with the very stiff 1<sup>st</sup> baseline 5 MW design rotor- Figure 6, right the mean root bending moment is reduced significantly by a factor 4.3. The chord is smaller for the 2<sup>nd</sup> baseline blade and for the same material thickness the second moment of inertia of the profile will be significantly less than for the larger chord used in the 1<sup>st</sup> baseline blade. However the reduced bending moment leads to a blade weight of 45,8 tons for the Case-2 blade design, which is less than a third of the blade weight for the 1<sup>st</sup> baseline design.

From Figure 6 it is seen that the mean normal forces along the sectionized blade arc are almost unaffected by air loads and that the variation has a pronounced effect due to blade rotation. From Figure 6, right it is seen that there is a difference between the magnitudes of the normal forces when comparing with the 2<sup>nd</sup> iteration results and that there is significant influence from the centrifugal force on the blade shape equilibrium with weight.

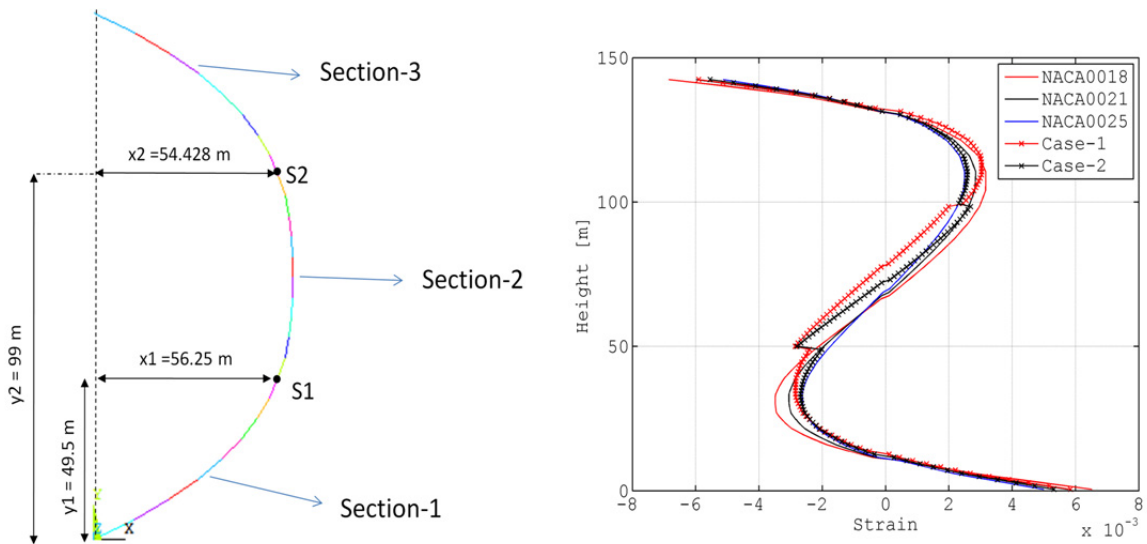


Figure 5 Left: Schematic of the sectionized rotor and right: the ANSYS calculations of the strain distributions for the sectionized rotor throughout the rotor for point A (see Fig. 3) which is located at the inner side of the rotor.



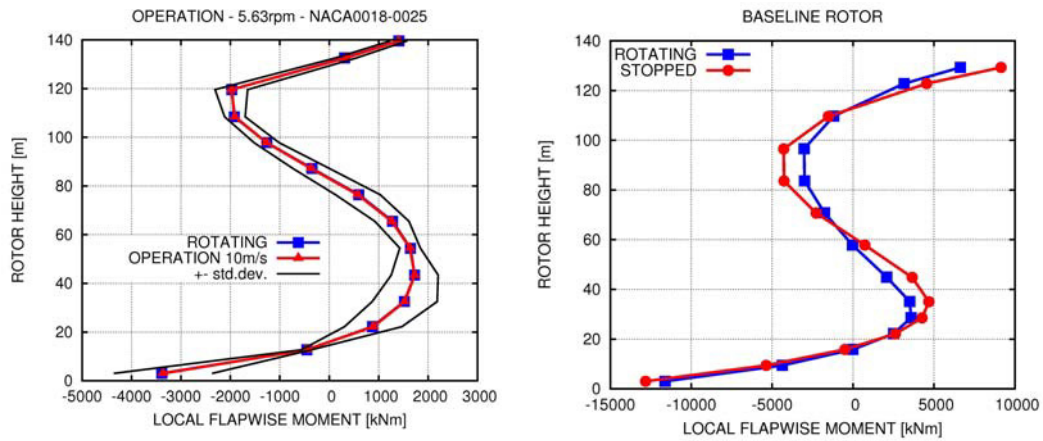


Figure 6 Case 2: Left : influence of operation on the flapwise moment from 2<sup>nd</sup> iteration and Right: on the 1<sup>st</sup> baseline 5 MW design

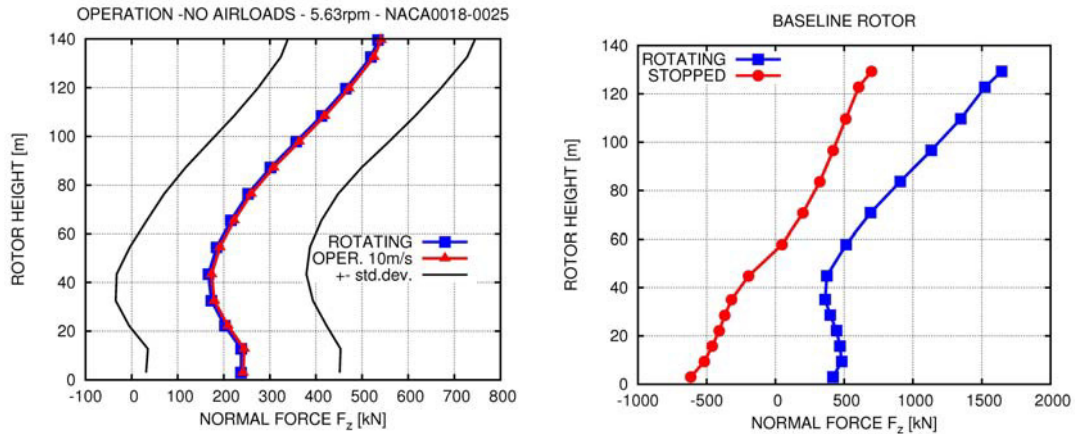


Figure 7 Influence of the operation on the normal force. Left: 2<sup>nd</sup> iteration results. Right: 1<sup>st</sup> baseline 5 MW Design

The results show that there may be potential ways to decrease the variations of the pulsations additionally within this project. However, with the above indications it has been investigated if the uniformity of the flapwise loads can be reduced additionally, by conducting a simulation with reduced flapwise stiffness and rerun the same rotor shape. The result is shown in Figure 8 left together with the flapwise loads, Figure 8 right, and in Figure 9.

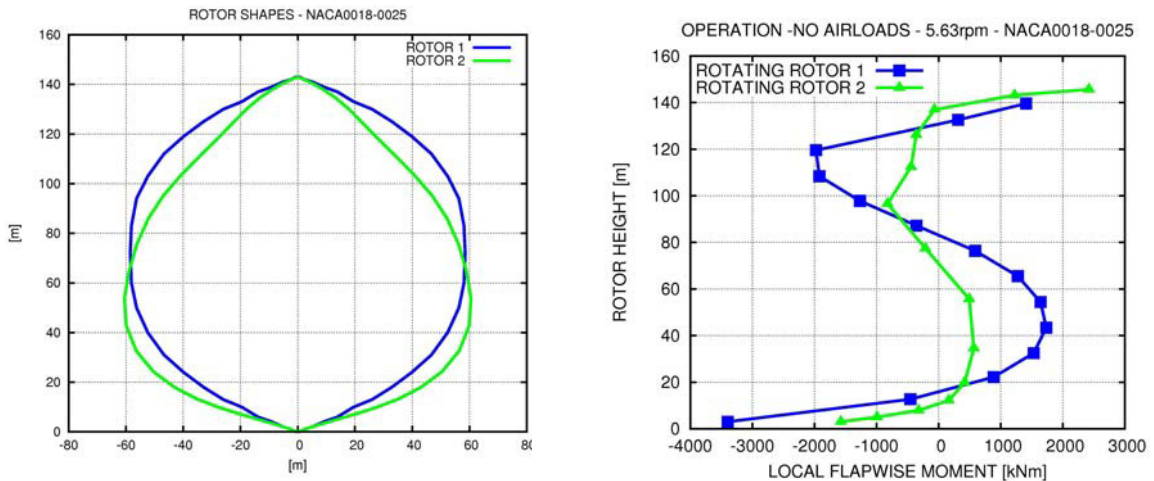


Figure 8 Influence of flapwise stiffness relaxation along the blade arc. Left: rotor shape of 2nd iteration (rotor1) and 3rd iteration(rotor2). Right: Flapwise loads during rotation.

As seen in Figure 8, right, the moment distribution is generally more uniform over a major part of the rotor, and from Figure 9 it is seen, that a bigger part of the loads are carried by tension as seen in the normal force distribution over the whole rotor.

The more uniform moment distribution could lead to the use of NACA 0018 over a bigger part of the rotor.

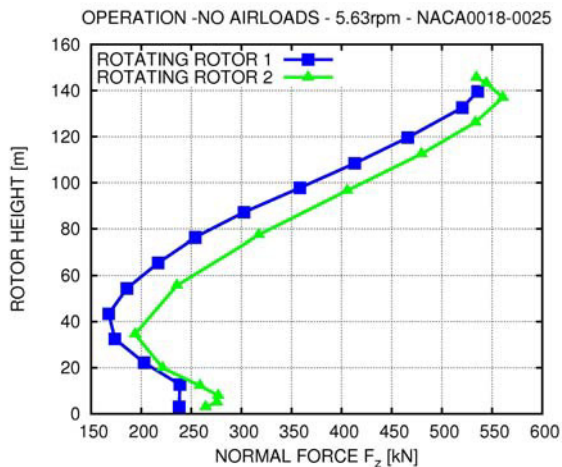


Figure 9 Consequences of blade stiffness relaxation on the 2nd iteration rotor design.

### 2.3. Consequences of design on the blade manufacturing process

For the uniform rotor, the blades, which are connected to the center tower at both ends, can be manufactured with constant chord. Hence, pultrusion technology which is one of the most cost efficient and suitable methods to manufacture constant cross section composite parts is a convenient way to manufacture the blades. These can be shaped into a troposkien shape where their flapwise (radial) bending stresses during

operation are reduced to essentially zero and the blades are loaded only in tension (see Figure 9), a very favorable loading scenario for composite materials [7]. A VAWT blade has already been manufactured by using the pultrusion process as reported in [7]. Regarding the possibilities of using the pultrusion process, several numerical modeling studies of the process have also been carried in the literature in connection with the DeepWind project<sup>7</sup> [8-13].

A sectioned rotor blade poses particular challenges in designing the joint between sections. Although the joints can be placed in regions of lower stresses compared to blade/rotor joint, other criteria such as weight and accessibility for maintenance has to be considered. This means the joint cannot be designed similar to the blade/rotor joint where a large supporting structure can be built on the rotor. Additionally the joint will add to weight and cost for the blade. Another possibility for a sectionized rotor would be a molding manufacturing process, e.g. resin transfer molding (RTM), and vacuum infusion etc., which would be possible techniques to produce the blades. The current ability of the wind industry for the design and construction of the reliable attachment joints (i.e., hub joints in HAWTs) in composite blades makes the molded composite blades an attractive design option [7]. However, the associated manufacturing cost is high as compared to the pultrusion process.

### 3. Conclusion

The present paper demonstrates the results of an optimization conducted on the DeepWind concept, considering rotor design. It is demonstrated that significant weight and load reductions on the rotor are achieved on a rotor with stall control and pultruded GRP blades.

### Acknowledgements

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<sup>7</sup> Baran I, Tutum CC, Hattel JH. *Probabilistic thermo-chemical analysis of a pultruded composite rod*. Proceedings of the 15th European Conference on Composite Materials, ECCM-15, Venice, Italy, 24-28 June 2012.

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