Structural Optimization and Scaling Trends of Vertical Axis Wind Turbine Rotors

M. Schelbergen, B. Roscher, L.O. Bernhammer ¹, E. Ferede, C.J. Simao Ferreira

Faculty of Aerospace Engineering, Delft University of Technology, Kluyverweg 1, 2629HS Delft, The Netherlands

Abstract

In this paper a structural optimization of multi-megawatt Vertical Axis Wind Turbine (VAWT) rotors is presented and scaling trends based on varying tower heights are derived. Structural optimizations of a three-bladed carbon-fiber H-rotor and Darrieus rotor have been performed for different rotor sizes and tower heights. The results were used to construct mass scaling trends for VAWT rotors. Furthermore, critical failure modes and their driving loads were identified.

When optimizing only for the blade mass and neglecting the tower design, an optimum diameter-to-height ratio of the H-rotor is found in the close to unity. This optimization is performed independent of other subsystems as the tower. The optimum diameter-to-height ratio of the Darrieus rotor lies below 0.5. The optimum rotor power for a 180m high H-rotor lies between 10 and 15MW. For the same rotor height, the optimum rotor size of the Darrieus rotor is significantly lower. More subsystems need to be evaluated in the optimization to make a solid conclusion on the overall optimum rotor size. A varying blade cross section distribution along the Darrieus rotor was implemented in a later stage. To allow sufficient variation of the diameter-to-height ratio of the rotor, optimizations are performed with a variable rotor height. This modification showed a reduction of the 5 MW Darrieus design objective by 20%.

Keywords: Vertical Axis Wind Turbines, Offshore, Structural

¹Corresponding author: l.o.bernhammer@tudelft.nl, +31 15 27 88092

Preprint submitted to Journal of Wind Engineering & Industrial Aerodynamics October 20, 2015
Optimization, Rotor Design Optimization, Scaling Trends

Introduction

The development of the offshore wind turbine market caused an increased interest in large wind turbines. Vertical axis wind turbines (VAWT) have some inherent characteristics which make them more suitable for a large scale, offshore application compared to horizontal axis wind turbines (HAWT). A VAWT does not require a yawing mechanism and heavy systems are located at the bottom of the turbine. For the floating VAWT new design solutions need to be incorporated to yield a cost-efficient design of 20 MW turbines. This paper evaluates the influence of the rotor size and shape on the structural rotor performance of multi-megawatt VAWT.

Most of the research on VAWT has been performed before the 90s. A substantial amount of this work focused on the structural dynamics of VAWT. The structural dynamics of the rotor including resonance are more complex due to the effects of a rotating frame. The paper of Schienbein and Malcolm (1983) shows that the structural response of the rotor is successfully predicted by including Coriolis effects, whirling softening and stress stiffening.

Research on the performance of VAWT rotor shapes also investigated the aerodynamic performance. Marini et al. (1992) investigated the performance of parabolic and conic-cylindrical rotor shapes. Their work shows that a parabolic blade, with given airfoil section and length, a diameter-to-height ratio in the range of 0.75 and 1 results in the best aerodynamic performance.

The comparative study of Eriksson et al. (2008) states that the blades of a HAWT are subject to a reversing cyclic load due to gravity. This cyclic load increases with the size of the turbine and is believed to be one of the main limiting factors for upscaling HAWT due to fatigue. In the blades of VAWT’s gravity does not cause a cyclic load. However, aerodynamic loads on the blade do cause reversing cyclic loads. It is believed, that the cyclic loads for VAWT are less severe for the fatigue life of the turbine compared to the cyclic loads.
for HAWT and therefore less of a limiting factor for further upscaling of wind turbines. Eriksson concludes that VAWT should be considered as an alternative to HAWT for large scale, offshore application.

For the European DeepWind project a 5MW stall controlled Darrieus turbine is designed to serve as a baseline design throughout the design process. The baseline design is presented in the paper of Paulsen et al. (2012). The resulting blade is 189m long, has a constant cross-section and constant material properties along the blade, and weighs 154,000kg. Alternative designs with varying cross section and material properties along the blade are being explored.

Raciti Castelli et al. (2013) developed a numerical method to perform a combined aerodynamic and structural analysis of a VAWT blade in an H-configuration. The emphasis of the paper is put on assessing the contributions of the aerodynamic and inertial loads to the stresses and deformations of the blade in normal operation. The results show that the contribution of the inertial load to the blade displacement dominantes over the aerodynamic load.

Floating turbines enable installing wind energy offshore at large water depths. During operation, gyroscopic motions occur because the floating rotor is tilted by the thrust. This increases the complexity of the structural dynamics of the rotor. Owens et al. (2014) conclude in their work that a monopile structure may exacerbate resonance, while a floating platform can alleviate resonance.

The objective of this paper is to establish scaling trends for large vertical axis wind turbines by optimizing the rotor design for power capacities up to 20 MW. Critical failure modes and driving loads are identified and used to identify possible design improvements. The scope of this paper is limited to the structural design of the rotor blades and struts; other substructures and systems of the turbine such as tower or generator are omitted in the optimization. The structural design of two different carbon-fiber rotor configurations are evaluated: a 3-bladed H-rotor and a Darrieus rotor, as shown in Figure 1.
1. Methodology

A case study is performed for both H-rotor and the Darrieus rotor. For each case, a structural optimization has been performed. The structural analysis of the rotor is performed using a Finite Element Method (FEM) analysis and a limited number of load cases and failure modes. A distinction is made between two types of optimization: a variable power and a fixed power optimization. Both optimization types use the same objective function and design variables. The variable power optimization uses a fixed rotor height and a variable projected rotor power. The fixed power optimization also uses a fixed height, however a constant projected rotor area is imposed by inequality constraints.

1.1. Definition of the structural model for the rotor optimization

For the numerical optimization, it is required to convert the design of the rotor structure into a mathematical representation. An approach based on Non-Uniform Rational Basis Splines (NURBS) is used to model the shape of the
turbine blades, as proposed by Ferede et al. (2013). This method requires a limited set of shape variables to generate the shape of the blade, which is useful for optimization purposes. The location of the control points of the NURBS become the design variables. The finite element analysis is performed using shell elements. Despite the limited set of shape variables, the method offers enough design freedom to vary the blade shape. The strut is modeled as a tapered cantilevered beam.

1.2. Definition of the structural model for the rotor optimization

For the numerical optimization, it is required to convert the design of the rotor structure into a mathematical representation. An approach based on Non-Uniform Rational Basis Splines (NURBS) is used to model the shape of the turbine blades, as proposed by Ferede et al. (2013). This method requires a limited set of shape variables to generate the shape of the blade, which is useful for optimization purposes. The location of the control points of the NURBS become the design variables. The finite element analysis is performed using shell elements. Despite the limited set of shape variables, the method offers enough design freedom to vary the blade shape. The strut is modeled as a tapered cantilevered beam.

The structural analysis has been carried out in the finite element software MSC/Nastran (Software 2011). The mathematical description of the rotor has been used to create an input file for the finite element analysis.

The mass increase of the blades is identified as a limiting factor for the upscaling of wind turbines. The use of carbon-fiber laminates in the blade design is considered as a good design solution to reduce mass despite the high material costs, as their specific stiffness helps reducing the gravitational loads. Therefore, carbon-fiber laminates are used during the optimization.

1.3. Evaluated load cases and failure modes in the optimization

The evaluated load cases in the optimization are limited to reduce the optimization time. Only parked conditions (P) and normal operation condition at
Table 1: Normal operation conditions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated wind speed</td>
<td>12 [m/s]</td>
</tr>
<tr>
<td>Tip speed ratio</td>
<td>4.5 [-]</td>
</tr>
</tbody>
</table>

Table 2: Safety factors

<table>
<thead>
<tr>
<th>Load case</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultimate</td>
<td>1.5</td>
</tr>
<tr>
<td>Fatigue</td>
<td>1.265</td>
</tr>
<tr>
<td>Limit</td>
<td>1</td>
</tr>
</tbody>
</table>

an upwind (UW) and downwind (DW) point in the blade rotation are considered. In Table 1 the operational parameters in normal operation are stated. For the normal operation condition, the structural analysis includes gravitational (Grav), centrifugal (Centr), and aerodynamic (Aero) loads. In the parked condition, the structural analysis considers gravitational loads only. The applied safety factors (SF) are taken from the work of [Ashuri 2012] and given in Table 2.

The aerodynamic loads are introduced to the blade as applied pressure distribution, which is obtained using the results of a 2D unsteady panel model simulation obtained with a potential flow solver. The evaluated upwind and downwind positions correspond to the azimuthal angles with the maximum and minimum normal force coefficient. The provided angles of attack are used in XFOIL [Drela and Youngren 2001] to obtain the pressure distribution at these azimuthal blade positions. It is assumed that the chordwise pressure distribution is uniform along the blade. The air velocity perceived by a blade segment is simplified to be a summation of the wind speed and the rotational speed. Combining the pressure coefficients with the local dynamic pressure yields the aerodynamic loads.

Table 3 states the evaluated failure modes per load case. The structure is analyzed for ultimate strength and buckling under ultimate load for both upwind and downwind position. At the downwind blade position the centrifugal forces and the radial aerodynamic forces act in the same direction, therefore the

\footnote{Results of an airfoil optimization, received on: 30-10-12 from Carlos Simao Ferreira.}
flapwise bending moment in the blade is expected to be largest at this position. The flapwise bending moment is assumed to drive the buckling failure of the structure. To limit the optimization time, buckling is only analyzed at the downwind position of the blade for the normal operation condition.

The fatigue analysis accounts only for the variation between the upwind and downwind position during normal operation conditions at rated wind speed. The fatigue analysis assumes the turbine is operating solely at rated wind speed for 35% of its 20 year life time. The rotational speed of the turbine depends on the rotor shape, since the tip speed ratio is kept constant. The product of the time in operation and the rotational speed yields the number of rotations the turbine needs to withstand in its life time.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Blade position</th>
<th>Evaluated failure modes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal operation</td>
<td>Downwind</td>
<td>Ultimate strength, buckling &amp; fatigue</td>
</tr>
<tr>
<td></td>
<td>Upwind</td>
<td>Ultimate strength &amp; fatigue</td>
</tr>
<tr>
<td>Parked</td>
<td>-</td>
<td>Ultimate strength &amp; buckling</td>
</tr>
</tbody>
</table>

1.4. Types of optimization

Two types of optimizations are performed, as stated in Table 4. First, fixed height optimizations are performed to thoroughly evaluate the designs. Second, multiple fixed power optimizations are performed to construct scaling trends. In the fixed height optimization the rotor size is variable. The fixed height optimization uses a baseline rotors as initial point, see Figure 5. The rotor power of the baseline H-rotor and Darrieus rotor are equivalent to respectively 9.0 MW and 5.2 MW.

Fixed power optimizations are performed for 3, 5, 8, 10, 15, and 20 MW and for 100, 140, and 180 m high rotors. Additionally, a 260 m tall Darrieus rotor is evaluated for a rotor power of 15 and 20 MW. The starting shapes are obtained
by scaling the geometric design variables of the baseline rotors to the correct rotor height and projected area.

Table 4: Optimization sequence

<table>
<thead>
<tr>
<th>Name</th>
<th>Axial segments</th>
<th>Fixed rotor size [MW]</th>
<th>Equivalent rotor area ([10^3 \text{ m}^2])</th>
<th>Fixed rotor height [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fixed height</td>
<td>blade: 5</td>
<td>-</td>
<td>-</td>
<td>H-rotor: 141</td>
</tr>
<tr>
<td>optimization</td>
<td>strut: 4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fixed power</td>
<td>blade: 5</td>
<td>3, 5, 8, 10, 6.6, 11.0, 17.6, 100, 140,</td>
<td>22.0, 33.0 &amp; 44.0</td>
<td>180 &amp; 260</td>
</tr>
<tr>
<td>optimization</td>
<td>strut: 4</td>
<td>15 &amp; 20</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

After these optimization showed satisfying results, the optimizer was modified such that the blade cross section height is varied along the Darrieus rotor. Thus allowing to have thick blade cross sections close to root, while locating thin profiles at the equatorial region. Meanwhile the solidity of the blade is kept constant, giving the possibility to compare results. The rotor mass can be further reduced, while the aerodynamic performance remains almost unaffected. The slender profiles allow to save mass, while the thicker profiles provide a structural reinforcement.

The blade cross section height is scaled depending on the local inflow of the section itself. If the blade cross section is oriented perpendicular to the rational plane, it will experience a wider range of angle attacks (Ferreira, 2009). These sections will be scaled to thicker profiles. This mostly happens close to the blade root. Depending on the range of the inflow angle the blade cross section is varied.

The addition to the optimization might lead to a change of the Darrieus rotor shape. Possible rotor shape can be found in Figure 2. The shape presented in Figure 2(c) is an alternative form the known H-rotor. Due to the scaling algorithm the optimizer might relocate the majority of the blade outwards. In this paper several thickness configurations at various tower heights are used in the optimization procedure. In two cases the blade section height will be
kept constant, such that a comparison can be taken. The rotor will have a representative size of 5 MW. The tower height is changed from 120 m to 180 m.

![Graphs showing different blade section height distributions.](image)

(a) Troposkien  
(b) Pulled down Troposkien  
(c) Alternative H-Rotor

Figure 2: Possible blade section height distribution with a design tip speed ratio of 4.5

1.5. Optimization algorithm

The optimization is performed in The MathWorks (2014). MSC Nastran is called to determine the stresses and buckling modes for the different loading conditions. The output of MSC Nastran is processed into optimization constraints, which are used by the optimizer to come to a feasible rotor design.

The optimization routine `fmincon` is used in Matlab. The `fmincon` routine searches a minimum of a constrained non-linear multi-variable function using a gradient-based method. The computational costs of the optimization are high, because a significant number of design variables are used in the optimization problem and detailed analyzes are performed to evaluate each design. A gradient-based algorithm is preferred to a genetic algorithm, since in general gradient-based optimizations have lower computational costs.
1.6. Optimization objective function

All proposed optimizations have the same goal: minimizing the cost of the rotor, while maximizing the energy yield of the turbine. The cost of the rotor is assumed to be a linear function of the rotor mass and thereby neglecting, among other parameters, the manufacturing costs of the rotor structure.

The power coefficient is assumed to be constant, by keeping the tip speed ratio and blade solidity (the blade chord over rotor radius ratio) constant. A constant power coefficient implies that the energy yield of the turbine is a linear function of the projected rotor area.

A constant power coefficient of 0.43 and a blade solidity of 0.067 is assumed. The latter assumptions imply that minimizing the cost of the rotor, while maximizing the energy yield of the turbine, is equivalent to minimizing the rotor mass over projected area ratio. The structural rotor performance is assessed by the value of this ratio.

Figure 3: Segment division of the FEM model of the rotors
1.7. Design variables of the optimization

The design variables of the optimization are divided in two categories: the thickness and shape variables. Both the blade and strut are divided into segments of equal length along their longitudinal axis for allocating the sizing variables. For the blade 5 segments are used and for the strut 4 segments, as shown in Figure 3.

The sizing variables of the blade are its laminate thicknesses. Per axial segment, one variable laminate thickness is used for each structural component. The cross section of the blade has three components: the girders, shear webs and skin, as shown in Figure 3(c). Carbon-fiber laminates have been designed for the specific function of each blade component.

The sizing variables of the strut are its laminate thickness and its cross sectional size. One variable laminate thickness is used per axial segment. Also for the strut a carbon-fiber laminate has been designed. The geometry of the cross section of the strut is varied at both ends by changing the width and height of the cross section. The cross section along the strut is varied linearly between the cross section at both ends. Both struts in the analysis of the H-rotor are identical.

The shape variables are used to define the blade axis, as shown in Figure 5. The H-rotor uses a straight blade, for which the radial position is varied. Furthermore, the vertical positions of the struts can be varied independently.

The Darrieus blade uses a curved blade; the blade curvature is varied by varying the radial position of 7 control points.

The chord length of the blade is not defined as a design variable. However, the chord length changes in the optimization, since it is set by the blade solidity. The solidity of the rotor is kept constant, the chord of the blade changes accordingly.

During the later modifications of the optimizer three blade cross section heights are defined initially along the blade. These are shown in Figure 4. The section height $t_{\text{root}}$ is defined at the blade-tower-connection. $t_{0.8}$ is the section height at which the local tip speed ratio is equal to 0.8. These two section heights
will be linear interpolated. The last configuration section height is \( t_{eq} \). This is the section height at which the inflow angle is aligned with the rotational plane. In the optimization procedure a the following cross section height distributions are used.

1. constant 18% of chord
2. constant 25% of chord
3. \( t_{eq} \): 15% of chord; \( t_{0.8} \): 40% of chord; \( t_{root} \): 50% of chord
4. \( t_{eq} \): 15% of chord; \( t_{0.8} \): 40% of chord; \( t_{root} \): 60% of chord
5. \( t_{eq} \): 15% of chord; \( t_{0.8} \): 40% of chord; \( t_{root} \): 70% of chord
1.8. Optimization constraints

The occurrence of failure is identified using failure indices (FI) for all load cases. In general, the failure index is determined by dividing the product of the occurring design load and the safety factor by the allowable load, see Equation 1. A failure index value higher than 1 indicates failures.

\[ FI = \frac{\text{Design load} \cdot SF}{\text{Allowable load}} \]  \hspace{1cm} (1)

The failure indices are translated to inequality constraints by subtracting 1, see Equation 2. A feasible design is indicated by values below zero for all inequality constraints.

\[ c_{ineq} = FI - 1 \]  \hspace{1cm} (2)

For the fixed power optimization, a fixed rotor size (power capacity) is imposed by keeping the projected rotor area constant. For the H-rotor, a given
projected rotor area and rotor height yields the rotor radius. For the Darrieus rotor, a constant projected rotor area is approximated by two inequality constraints.

2. Optimization results

2.1. Fixed height optimization results

The results of the fixed height optimizations are stated in Table 5. For both the H-rotor and Darrieus rotor the critical failure modes are local buckling and fatigue damage. For the H-rotor, the highest fatigue damage is found in the girders and in the skin of the blade towards the tip with respect to the strut connection, see Figure 8(a). At this position the border of two blade segments is located. In the normal operation condition, buckling first occurs in the blade at the border of two blade segments just above the upper strut connection, see Figure 7. For the Darrieus rotor, high values for the fatigue damage are found at the roots of the blade and sections with a high blade curvature, see Figure 8(b). Blade buckling first occurs close to the upper segment border in the normal operation condition.

In Figure 9, Figure 10, and Figure 11 the internal bending moments and deflection of the structures are shown for respectively the H-rotor blade, the H-rotor strut, and the Darrieus rotor blade. The bending moment and deflection are decomposed to quantify the contribution of the centrifugal, aerodynamic, and gravitational load to the total.

2.2. Scaling trends

A second optimization has been performed to obtain scaling trends of the vertical axis turbine. A fixed area optimization has been performed with the same design variables as in the fixed height optimization, however with the additional constraint that projected rotor area remains constant during the optimization. The rotor designs resulting from the fixed power optimizations are used as data points to which a curve was fitted. The values of the optimization
Table 5: Fixed height optimization results

<table>
<thead>
<tr>
<th>Property</th>
<th>H-rotor</th>
<th>Darrieus rotor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Projected rotor area [m²]</td>
<td>18,060</td>
<td>10,287</td>
</tr>
<tr>
<td>Equivalent power [MW]</td>
<td>8.2</td>
<td>4.7</td>
</tr>
<tr>
<td>Diameter [m]</td>
<td>128.1</td>
<td>110.7</td>
</tr>
<tr>
<td>Diameter-to-height [-]</td>
<td>0.91</td>
<td>0.77</td>
</tr>
<tr>
<td>Blade mass [kg]</td>
<td>16,040</td>
<td>10,611</td>
</tr>
<tr>
<td>Strut mass [kg]</td>
<td>2760</td>
<td>-</td>
</tr>
<tr>
<td>Rotor mass over area [kg/m²]</td>
<td>3.58</td>
<td>3.09</td>
</tr>
</tbody>
</table>

Maximum FI
- Ultimate strength UW [-]       | 0.46    | 0.57           |
- Fatigue [-]                     | 0.99    | 0.98           |
- Ultimate buckling DW [-]        | 1.08    | 0.97           |
- Ultimate buckling P [-]         | 0.80    | 0.81           |

The points minimizing the objective function for the power capacity are connected by the dashed line. During the optimization it was found that local buckling as shown in Figure 7 at element intersections and around the strut-blade attachment was constraining the optimization space, the penalty function associated with the buckling failure index was relaxed. This relaxation is believed to be possible as local panel buckling is an artifact of the shell formulation of the optimization problem and can in a real design easily be solved by adding a lightweight web between the composite layers. In Figures 12(a) and 12(b) points which violate the buckling constraints with more than 5% are marked. Upon severe violations such as occurring for the 8 and 10MW cases with 100 or 140m blade length, the optimization results have been disregarded. The dashed line illustrates the lower boundary of the optimization objective. The rotor designs corresponding to the lower boundaries of the optimization objective versus the power capacity are referred as the best rotor designs. These
rotor designs are amongst others used to construct the mass scaling trends.

In Figure 13(a) and Figure 13(b) the optimization objective is plotted against the diameter-to-height ratio to identify which diameter-to-height ratio minimizes the objective function. The optimum diameter-to-height ratio might also be a function of the rotor size. Therefore, Figure 14(a) and Figure 14(b) are used to evaluate the diameter-to-height ratio corresponding to the best rotor designs versus the rotor size.

Figure 15(a) and Figure 15(b) show the failure indices of the best rotor designs for respectively the H-rotor and the Darrieus rotor. These figures are used to evaluate which failure modes are expected to occur first for different rotor sizes and therefore are critical.

The work of Ashuri (2012) presents optimized 5, 10, and 20 MW HAWT, for which he minimized the cost of energy. The corresponding scaling trend is:

\[ m_{\text{blade}} = 0.0571 \cdot D^{2.64} \]

This scaling trend has been rewritten as a function of the power capacity, assuming constant \( c_P \) for all HAWT, such that it can be
compared to resulting VAWT trends.

The VAWT mass scaling trends are constructed using a power curve fit: $aP^b$, in which $a$ is the curve coefficient, $b$ is the curve exponent, and $P$ is the power capacity. Figure 16 shows the mass scaling trends of the H-rotor and Darrieus rotor. Additionally, the mass scaling trend of a HAWT rotor from the work of Ashuri is included in the graph. In Figure 17(a) and Figure 17(b), the total mass of the H-rotor and Darrieus rotor is decomposed in the masses of the substructures to evaluate their mass contribution as function of the rotor power.

2.3. Results of the modified optimization with aerodynamic influence

In the following subsection, the results of the modified optimizer are presented. Figure 18 displays the determined rotor mass over rotor areas. The plus sign represents the 120 m tower height, the diamonds the 150 m and the stars the 180 m tower height. It can be seen that for all optimization setups the height of 150 m produces the lowest function values. At the tower height of 120 m the objective values are just shifted upwards. The objectives of the 180 m height display a linear decreasing trend. The last blade section contribution ($t_{eq}$: 15% of chord; $t_{0.8}$: 40% of chord; $t_{root}$: 70% of chord) is even lower than the 120 m objective. This rotor mass to rotor area ratio is just a bit bigger than the one with the 150 m tower. It can be noted that the output of the constant blade
cross sections heights have the greatest objective value independent of the turbine heights. The overall best performance was achieved with tower height of 150 m and a blade cross section height contribution where \( t_{eq} \) is 15% of chord, \( t_{0.8} \) 40% of chord and \( t_{root} \) 60% of chord.

The blade curvatures of the optimizations with variable blade cross sections are shown in Figure 19. The dashed line is equal to the design where \( t_{eq} \) equal 15% of chord, \( t_{0.8} \) 40% of chord and \( t_{root} \) 50% of chord. The dot-dashed line is
Figure 9: Decomposition of the internal loads and deflections of the H-rotor blade

the variable blade section with a $t_{\text{root}}$ of 70% of the chord. The solid black line represents the design with the lowest mass to area ratio and a $t_{\text{root}}$ of 60% of the chord. All three shapes have the blade have an increase in rotor radius. The shape is partially similar to the one in Figure 6(b). Here, the blade curvature has of these optimizations has a larger region, where the blade is located at maximum rotor radius. This indicates the effect of the variable blade cross section height.
Figure 10: Decomposition of the internal loads and deflections of the (lower) H-rotor strut

3. Discussion of the results

3.1. Identification of the critical failure modes and driving loads of the H-rotor

The scaling trends of the failure indices show that fatigue damage and buckling (DW & P) are the driving failure modes for both rotor configurations, as shown in Figure 15(a) and Figure 15(b). Buckling in normal operation (DW) tends to be the critical failure mode for the H-rotor and fatigue for the Darrieus...
Figure 11: Decomposition of the internal loads and deflections of the Darrieus rotor

Figure 12: Structural performance versus rotor power
3.1.1. Local failure modes

Both in the blade and strut of the H-rotor, the dominant form of buckling is local buckling. The buckling is occurring close to the border of two segments, where a step change in laminate thickness one segment to the other occurs, as seen in Figure 7. The loads on adjacent skin panels belonging to different segments are similar. However, the performance against buckling is smaller for the panel with the smaller thickness. In a real wind turbine design, this problem can be easily avoided by varying the thickness more continuously or by adding...
Fatigue is also occurring locally in the H-rotor blade; close to segment borders and the strut connection, as can be seen in Figure 16. In the optimization, fatigue damage is reduced by increasing the laminate thickness of a whole segment, which is suboptimal in terms of weight. The same holds for the Darrieus rotor, both buckling as fatigue damage occur locally but result in an increase of a whole blade segment in the optimization.
3.1.2. Driving loads of the H-rotor

The optimization mechanism of the H-rotor optimization is studied by determining the relation of the rotor radius and the loads. In this study, the laminate thicknesses are not changed and a uniform distribution of the laminate thicknesses is assumed along the blade length. The mass-per-length of the blade is therefore a linear function of the chord. The tip speed ratio, blade solidity and projected rotor area are assumed to be constant. Furthermore, the study assumes that the blade loads are the only contributors to the bending moments in the strut.

After substituting the constant tip speed ratio and blade solidity condition,
the expression for the radially distributed load due to centrifugal forces shows that it is independent of the radius. The radially and tangentially distributed aerodynamic loads are a linear function of the radius, just as the vertically distributed load due to gravity. From the radially distributed load, it follows that the flapwise bending moment in the blade is proportional to the radius to the power -1 and -2. In the strut, the edgewise and flapwise bending moments are a linear function of the radius.

Figure 20: Fatigue damage in the H-rotor blade per blade component
The general critical failure mode for the H-rotor is local buckling, however for smaller radii also fatigue damage becomes an active constraint. In combination with the simplified study this implies that local buckling in the strut becomes critical for an increase in the diameter-to-height ratio with respect to the optimized diameter-to-height ratio. Furthermore, it implies that buckling and fatigue damage in the blade become critical for a decrease in the diameter-to-height ratio. Notice that in the optimization the mass-per-length of the blade is also a function of the laminate thicknesses. Nevertheless, the simplified analysis gives a good indication about the effect of the rotor radius on the driving loads and critical failure modes with respect to the situation for an optimized design.

For the H-rotor blade, the difference in the bending moment due to the upwind and downwind aerodynamic load is driving the fatigue damage. The results of the fixed height H-rotor optimization show that the maximum difference in blade flapwise bending moment is more than one order of magnitude larger than the maximum difference in blade edgewise bending moment, see Figure 9. The difference in stress amplitude in the blade due to the flapwise and edgewise bending moment is even larger, as the flapwise bending stiffness is much lower than the edgewise bending stiffness. Therefore, the difference in blade flapwise bending moment is identified as the major fatigue driver in the H-rotor.

The results of the fixed height H-rotor optimization show that the maximum strut edgewise bending moment is about twice as large as the flapwise bending moment, see Figure 10. Therefore, the strut edgewise bending moment is identified as the major buckling causing load in the H-rotor strut. The aerodynamic load is the only contributor to the edgewise bending moment. In the blade, the flapwise bending moment is causing the structure to buckle first around the girders. The major buckling causing load in the H-rotor blade is therefore the flapwise bending moment.
Figure 21: Cyclic, axial stress in a FEM element at the trailing edge and upper root of the Darrieus blade

3.1.3. Driving loads of the Darrieus rotor

The difference in bending moment in the H-rotor blade due to the aerodynamic load in upwind and downwind position is driving the fatigue damage. For the Darrieus blade, both the flapwise and edgewise bending moment contribute to the fatigue damage. The difference in flapwise bending moment is the major contributor to the fatigue damage at the sections with large blade curvature. In Figure 22 it can be seen that the peaks in the curvature result in large fatigue damage in the girders, which carry most of the flapwise bending moment. The difference in edgewise bending moment is the major contributor to the fatigue damage at the roots of the blade and is caused by torque ripple. The fatigue damage due to the difference in edgewise bending moment is underestimated in the optimization, since the fatigue analysis does not account adequately for torque ripple. The fatigue analysis assumes a single stress cycle in one blade revolution and uses the stresses at the upwind and downwind position to determine the stress cycle amplitude. In Figure 21 it can be seen that these positions correspond to the maxima of the stress cycle and therefore underestimate the stress cycle amplitude. Furthermore, the figure shows that there are two stress cycles per blade revolution.

The flapwise bending moment is primarily carried by the girders and is driving the buckling failure index of the Darrieus blade. The results of the fixed
height Darrieus rotor optimization show that, in normal operation at the downwind blade position, buckling first occurs in the girders at approximately 25 m below the upper blade end, at the border of two segments. At this position, the flapwise bending moment due to the gravitational, centrifugal, and aerodynamic load are all positive. The aerodynamic load is identified as the major buckling causing load, since it is the major contributor to the total bending moment.

The flexibility of the Darrieus blade shape allows alleviating the internal blade loads. This can be clearly observed when looking at the contributions of the flapwise bending moment at the outboard blade segment in Figure 11(a). The contributions of all the loads fluctuate around zero. In the outboard blade segment, the contributions of the centrifugal and aerodynamic load have a weaker negative relation with the rotor radius than the H-rotor. In contrast, the contribution of the gravitational load and the rotor radius have a stronger positive relation than the H-rotor. Therefore, the Darrieus rotor is expected to converge to a relatively lower diameter-to-height ratio than the H-rotor.

3.2. Optimum rotor size

Figure 12(a) and Figure 12(b) are used to identify the optimum rotor sizes for specific rotor heights of the H-rotor and Darrieus rotor. In Figure 12(a), the curves for the 140 and 180 meter high H-rotor are convex. For these rotor heights, the minimum of the objective function is believed to lie in the analyzed
domain of the rotor power capacity. In Figure 12(b), none of the constant rotor
height lines for the Darrieus rotor show a minimum. It is believed that for the
100, 140, and 180 m high rotors, a minimum of the objective function can be
found below 3 MW. Taller Darrieus rotors are expected to have their optimum
rotor size, minimizing the objective function, lying inside the analyzed domain
of the rotor power capacity.

Besides the optimum rotor size for a specific height, Figure 12(a) and Figure
12(b) can be used to search for the overall optimum rotor size and the cor-
responding rotor height. In search of the optimum, the lower boundaries of
the optimization objective are studied (dashed lines in Figure 12(a) and Figure
12(b)). For both the H-rotor and Darrieus rotor, the lower boundary of the
optimization objective shows a positive slope throughout the analyzed domain.
The positive slope implies that the optimum rotor size can be found below
3 MW. Taller rotors should be evaluated more extensively to further reduce the
objective function for rotor size larger than 10 MW. Including taller rotors will
thereby flatten the lower boundary of the optimization objective in Figure 12(a)
and Figure 12(b).

3.3. Optimum rotor shapes

The optimum rotor shape is quantitatively studied using the the diameter-to-
height ratio. Figure 13(a) and Figure 13(b) show the objective function versus
the diameter-to-height ratio of the H-rotor and Darrieus rotor. These figures are
used to search for a diameter-to-height ratio minimizing the objective function.

For the H-rotor, the curves of the 140 and 180 meter high rotor seem to be
convex. For these rotor heights, the minima of the objective function lies in the
analyzed domain of the diameter-to-height ratio. The 100 meter high rotor is
evaluated for relatively high diameter-to-height ratios. More points need to be
evaluated for this rotor height to accurately identify a possible minimum.

Also, the curves of the Darrieus rotor need more points to identify a possible
minimum. The minima of the objective function can be found for diameter-
to-height ratios lower than the analyzed diameter-to-height ratios. Notice that
low diameter-to-height ratios look promising for the Darrieus rotor design on a subsystem level, but may yield poor performance on a system level. For example a decrease in the diameter-to-height ratio increases rotor tower length, which can have an adverse effect on the cost of energy.

In Figure 14(a) the optimum diameter-to-height ratio seems to fluctuate around 1 for the H-rotor. All the evaluated points are displayed to show the restrictions of identifying the optimum rotor designs for the power capacity. Many of the rotor designs show a buckling constraint violation of more than 5%. The designs that do not violate the buckling constraint with more than 5% have a diameter-to-height ratio close to 1. This implies that other values for the diameter-to-height ratio impose difficulties in meeting the structural requirements, a value close to 1 is therefore preferred.

In Figure 14(b) the optimum diameter-to-height ratio scaling trend for the Darrieus rotor is illustrated by the dashed line. In this case, the evaluated rotors with a relatively low diameter-to-height ratio appear to be the optimum rotor designs. However, data points for lower diameter-to-height ratios are missing. This makes it hard to identify an optimum diameter-to-height ratio for the Darrieus rotor. Notice that only the 15 and 20MW Darrieus rotors are evaluated for a 260 m rotor height. For these rotor sizes, the additional evaluated rotor height provides more variation in the diameter-to-height ratio of the optimized Darrieus rotors, which can affect the scaling trends of the Darrieus rotor.

From Figure 6(a) it can be observed that the struts are positioned more towards the tips with respect to the initial shape. Moving the struts more towards the tips decreases the maximum bending moment in the blade and can thereby contributes to meeting the structural requirements. From Figure 6(b) it can be observed that in the optimization the blade shape of the Darrieus rotor moves from a asymmetric blade shape to a near symmetric shape with respect to the midplane.

A similar behavior is also given in Figure 19 where the majority of the blade is moved towards the maximum rotor radius. A clear rectangular, similar to Figure 2(c) is not found. But the blade shapes indicates a trapezoidal
likely shape without any sharp corner. These corners would lead to a stress concentration which would need to be reinforced by additional material.

3.4. Relative mass contribution of the substructures

For the H-rotor, the scaling trend of the struts shows a significantly higher curve exponent than the blade components, as can be seen in Figure 17(a). This implies that the mass of the struts grows faster than the mass of the blade components. Therefore, the mass contribution of the struts gets more dominant for an increase in power capacity. In contrast, the mass contribution of the girders gets less dominant for an increase in power capacity. Although the relative mass contribution of the girders decreases, the girders remain the heaviest blade components for a 20MW rotor.

For the Darrieus rotor, the curve exponent of the shear web mass scaling trend is significantly larger compared to the curve exponent of the girders and skin mass scaling trends. Despite the large blade curve exponent, the shear web remains the lightest blade component for the analyzed domain of the rotor power capacity, as seen in Figure 17(b). Except for the curve exponent of the skin, the curve exponents of the blade components are significantly higher for the Darrieus rotor than for the H-rotor.

3.5. Comparison of the VAWT and HAWT mass scaling trends

Since the cyclic load in VAWT is not an inertial load, inertial loads are less of a limiting factor for further upscaling of VAWT rotors. The limit of upscaling can be assessed by the curve exponent of the mass scaling trend. The value for the curve coefficient of the scaling trend has a small impact on the limit of upscaling. As long as the curve coefficients of two mass scaling trends are of the same order of magnitude, it is justified to compare the trends solely by the curve exponent. The scaling trends resulting from the fixed power optimizations are shown in Figure 16. The curve exponent of the Darrieus rotor and H-rotor are lower than that of the HAWT rotor as calculated by Ashuri (2012). Based on these observations, it is believed that the limit of upscaling for the HAWT
rotors is found at lower sizes than for the VAWT rotors. Notice that a design of a different material would not only impose a change in curve coefficient, but also a change in curve exponent.

3.6. Possible rotor design improvements for 20 MW rotors

With respect to the outboard segment of the Darrieus blade, the inboard segment carries large flapwise and edgewise bending moments. Therefore, from a structural point of view, a significantly larger moment of inertia of the blade cross section should be allowed in the design at the inboard segment. This is enabled by controlling the cross section shape. From Figure 18 it can be extracted that the variable cross section results into a significant mass reduction independent of the tower height. While comparing the 5 MW results of Figure 18 with Figure 12(b) it can be noted that the variable blade cross section reduced the design objective by 20%. It also yields to a mitigation of the fatigue damage and buckling. It was also observed that size of the root cross section has a minimum at 60% of chord. Further improvements of the design objective and a reduce fatigue load are expected by allowing a variable chord length.

For the H-rotor the fatigue damage and buckling in the blade could be mitigated by reducing the flapwise bending moment contribution due to the aerodynamic load at the strut connection. One possibility is to use a variable chord length or airfoil thickness along the blade length. Using a relatively small chord length at the blade tip reduces the aerodynamic load far away from the strut connection and thereby the flapwise bending. Furthermore a larger chord length at the strut connection can reduce the stresses due to bending by the increase in moment of inertia.

For the 20 MW H-rotor, the strut becomes an important contributor to the rotor mass. To reduce the strut mass, the buckling performance of the strut should be improved. Other cross section shapes than a rectangular cross section should be explored. Such a cross section shape could for example include stringers.
Conclusions

Local buckling in normal operation, at the downwind blade position, is the critical failure mode for the H-rotor and fatigue for the Darrieus rotor. For a decrease in the diameter-to-height ratio, the flapwise bending moment gets more dominant at the outboard structure of the rotor. Vice versa, the edgewise bending moment gets more dominant at the inboard structure of the rotor for an increase in the diameter-to-height ratio. For example for the H-rotor, this results in a relatively high mass contribution of the blade with respect to the struts at small diameter-to-height ratios.

The optimum diameter-to-height ratio of the H-rotor is found in the neighborhood of 1. The optimum height of the Darrieus rotor tends to be higher than that of the H-rotor for the same rotor size. From the blade perspective, the optimum diameter-to-height ratio of the Darrieus rotor lies below 0.5. However, such low values would yield costs penalties on a system level.

The contribution of the aerodynamic load in the evaluated carbon-fiber rotors is relatively high compared to the expected contribution in a fiberglass rotor. Therefore, the effect of the gravitational load is less dominant in the resulting optimum shape of the Darrieus rotor. The optimum shape of the Darrieus rotor with a dominant gravitational load using glass fibres, makes the shape resemble the contour of a water drop. The optimizations of the carbon-fiber Darrieus rotor result in a near symmetric shape with respect to the midplane. The H-rotor optimizations show that the struts tend to move towards the blade tips, in order to reduce the flapwise bending moment in the blade.

The fatigue in the rotor structures in normal operation is induced by the aerodynamic loads. The reversing normal aerodynamic load on the blade induces high fatigue damage in the H-rotor blade at the connection with the strut. In the blade of the Darrieus rotor, sections with high blade curvature induce high fatigue damage.

The optimum rotor size of a 180m high H-rotor is expected to lie between 10 and 15MW. Therefore for a 20MW turbine, higher rotors need to be evaluated.
The optimum 20MW Darrieus rotor shape is expected to be even higher than that of the H-rotor. From the blade perspective, the overall optimum rotor size, independent of the rotor height, can be found below 3MW for both the H-rotor and Darrieus rotor. This result is not representative on a system level. More subsystems need to be evaluated in the optimization to make a solid conclusion on the overall optimum rotor size.

A rotor design using blade segments with constant wall thickness along the length is inherent to high stress concentrations in the rotor structure, which result in local failure due to fatigue and local buckling. A smoother distribution of the laminate thicknesses along the blade length imposes a more efficient way to cope with local failure modes in the optimization.

A variable cross section shape and chord length of the rotor blades can further reduce the blade mass by allowing a relatively high moment of inertia at highly loaded blade segments. The buckling performance of the H-rotor strut should be improved for a further strut mass reduction by controlling the cross section shape of the strut. A better buckling performance of the strut becomes increasingly important for larger rotors, since the strut mass becomes more dominant for higher power capacities.

References


Ferde EA, Abdalla MM, Bussel GJWV. NURBS-based Parametric Modelling

Ferreira CJS. The Near Wake of the VAWT. Ph.D. Thesis; Delft University of Technology; The Netherlands; 2009.


