

A Non-Linear Upscaling Approach for Wind Turbines Blades Based on Stresses

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Abstract:

The linear scaling laws for upscaling wind turbine blades show a linear increase of stresses due to the weight. However, the stresses should remain the same for a suitable design. Application of linear scaling laws may lead to an upscaled blade that may not be any more a feasible design.

In this paper a non-linear upscaling approach is presented with the aim of keeping the stresses in the upscaled blade the same as the reference blade. The stresses due to the weight, aerodynamics and centrifugal forces are taken into account and the blade is modeled as a beam with equivalent structural properties.

This new methodology is used to upscale the 5 MW NREL wind turbine blade to a 20 MW wind turbine blade. As a result, a 20 MW wind turbine blade is obtained in which the stresses are the same as the 5 MW blade. This provides initial blade design solution for optimization studies that is feasible and enables the designer to explore other interesting aspects of larger scale wind turbines.

Keywords

Wind turbine's blade design, Non-linear scaling law, Blade's aeroelasticity, Upscaling.

1. Introduction

The global demand for renewable energy and more specifically wind energy is growing continuously. However, the cost of generated electricity from wind turbines still

needs further reduction that forces the designers to search for better design solutions, which are more cost-efficient.

During the last two decades, wind turbines have been growing in size from 25 m rotor diameter to 125 m, and from a rated power of 250 kW to 5 MW, respectively. The wind energy industry demands the development of even larger machines to decrease the total cost. This is especially important for offshore wind farms where the largest wind turbines will operate.

A reasonable way to start the design of larger wind turbines is to use existing wind turbines as a starting point and upscale them. This shows how the current wind turbines behave in larger scales and makes it possible to analyse their advantages and disadvantages, and accordingly propose design improvements. In this way, all the experience and knowledge gained over many years is reflected in the design of this enlarged machines.

The existing upscaling practice for wind turbines is to use the linear scaling laws [1, 2]. This means upscaling all the geometrical dimensions of a reference wind turbine linearly to obtain the dimensions of the new upscaled machine.

For the blade, this approach shows a linear increase of the edgewise stress due to the weight of the blade, while the aerodynamics and centrifugal related stresses remain the same. This means that the upscaled blade experiences higher stresses, which results in a reduced lifetime.

However for a suitable design the upscaled blades must have the same level of

stresses as the reference blade. If not then the upscaled blade may not be anymore a feasible design.

This paper presents a new method to upscale the wind turbine blades, while maintaining the same level of all stresses in the upscaled blade with respect to the reference blade.

This goal is achieved by introducing an integro-differential equation in the upscaling procedure which relates the stresses along the reference and the upscaled blade.

By solving this equation, the constraint that the maximum stresses over both blades are the same can be satisfied. This generates an upscaled blade that has the same level of stresses as the reference blade.

The stresses are computed by modeling the blade as a beam with equivalent structural properties [3]. The aerodynamic loads over the blades are obtained from the aeroelastic code HAWC2, which simulates the reference turbine and the upscaled wind turbines independently.

The method quantifies the changes in the maximum stresses over the beam using the reference blade as a basis and it finds iteratively a new blade structural thickness for the upscaled blade which fulfills the constraint of maintaining the same level of stresses.

The approach is applied on the 5MW NREL wind turbine blade to find the blade of a 20 MW wind turbine [4]. The external shape of the blade that is defined by the chord and twist distributions along the blade is obtained by the linear scaling laws. The internal thickness distribution of the beam element that has two shear webs and two spar caps that are surrounded by a shell is calculated using the non-linear scaling laws.

A comparison between the maximum stresses along the blade for the linear and the non-linear upscaling approach is presented where the non-linear upscaling shows a reduction of the stresses in the blade to keep the same level of stresses during the process.

2. Methodology

2.1 Definition of the Upscaling Method

The non-linear upscaling approach can be carried out by defining a function with an unknown quantity called the non-linear upscaling function, which is found iteratively.

The values of this function vary along the blade. For a fixed radial position all the corresponding properties of each section are defined as the multiplication of the non-linear upscaling function and the linear upscaling ratio b . The idea is shown in the figure 1.

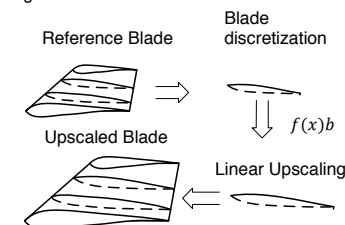


Figure 1: Upscaling of a reference blade using the non-linear upscaling function. Variable x is the radial position.

The function f enables the upscaling of the structural properties of the reference blade. Using this definition, the non-linear upscaling methodology is formulated as an integro-differential equation, which is a function of the non-linear function. By solving this integro-differential equation iteratively, the structural properties of the upscaled blade along the radial positions can be found.

2.2 Critical Operational Point and Loads

The loads considered in this work are determined at several wind speeds from the cut-in to cut-out wind speeds in the reference wind turbine and at the upscaled wind turbine using aeroelastic simulations in HAWC2. Then the highest loads are

selected based on the results of the aeroelastic simulations.

Three types of loads are considered to define the stresses. Edgewise loads, related to the weight of the blade, aerodynamic loads acting in the flapwise direction and the centrifugal force related to the rotation of the blade.

Respectively, edgewise, flapwise and axial stresses are considered. This is a constraint of the beam formulation, since the shear stresses or bend-twist coupling can not be modelled using such an equivalent formulation (for more information please see [3]).

In this work, it is assumed that the highest loads on the blade occur when the blade is in a level azimuthal position. Here, the highest stresses are expected due to the high contribution of the moment produced by the weight of the blade. This is shown in figure 2.

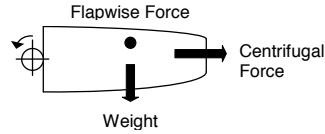


Figure 2: Loads acting on the blade at the level azimuthal position.

2.3 Upscaling Procedure

The upscaling methodology consists of seven steps:

1. The size of the tower and the rotor diameter for the upscaled wind turbine are determined for the desired power following the linear upscaling rules [1, 2, 5]. The linear upscaling ratio b is defined as:

$$b = \frac{D_2}{D_1} \quad (1)$$

Where D_1 and D_2 are the rotor diameters of the reference blade and the upscaled blade respectively.

2. The structural model of the reference wind turbine blade is defined as an

equivalent beam with equivalent structural properties [3].

The calculation of the stresses is done by assuming that their maximum occurs at the outboard part of each section measured from the neutral line.

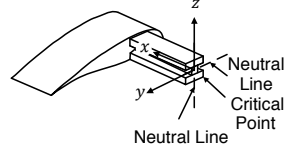


Figure 3: Equivalent beam for structural properties calculation

Using the structural properties of the blade, it is possible to determine the stresses in the reference beam as a function of the radial position variable x . Thus, the expressions for the stresses in the reference beam are:

$$\sigma_{1,w}(x) = \frac{g \int_x^R x \rho_l(x) dx}{W_z(x)} \quad (2)$$

$$\sigma_{1,cen}(x) = \frac{\omega_1^2 \int_x^R x \rho_l(x) dx}{A_1(x)} \quad (3)$$

$$\sigma_{1,aer}(x) = \frac{N_{1,1} + N_{1,2}}{2W_y(x)} \quad (4)$$

$$N_{1,1} = \omega_1^2 \int_x^R \rho_a C_{z,1}(x) x^3 c(x) dx \quad (5)$$

$$N_{1,2} = V^2 \int_x^R \rho_a x C_{z,1}(x) c(x) dx \quad (6)$$

Where:

$\sigma_{1,w}$: Stress in the reference beam due to the weight.

$\sigma_{1,cen}$: Stress in the reference beam due to the centrifugal acceleration.

$\sigma_{1,aer}$: Stress in the reference beam due to the flapwise aerodynamic force.

ρ_a : Air density.

ρ_l : Linear mass density of the reference beam.

ω_1 : Rotational speed of the reference blade.

c : Chord.

V : Wind velocity.

g : Gravity acceleration.

W_y : Section modulus of the beam about y axis.

W_z : Section modulus of the beam about z axis.

R : Radius of the reference blade.

A_1 : Sectional area of the reference beam.

3. The structural properties of the upscaled blade are formulated as a function of the non-linear function f , the linear upscaling ratio b and properties of the reference blade.

The expressions for the stresses in the upscaled beam are:

$$\sigma_{2,w}(f(x), x) = \frac{bg \int_x^R x f(x)^2 \rho_l(x) dx}{f(x)^3 W_z(x)} \quad (7)$$

$$\sigma_{2,cen}(f(x), x) = \frac{\omega_2^2 b^2 \int_x^R f(x)^2 x \rho_l(x) dx}{f(x)^2 A_1(x)} \quad (8)$$

$$\sigma_{2,aer}(f(x), x) = \frac{N_{2,1} + N_{2,2}}{2f(x)^3 W_y(x)} \quad (9)$$

$$N_{2,1} = \omega_2^2 b^2 \int_x^R \rho_a C_{z,2}(x) x^3 c(x) dx \quad (10)$$

$$N_{2,2} = V^2 \int_x^R \rho_a C_{z,2}(x) c(x) x dx \quad (11)$$

Where:

$\sigma_{2,w}$: Stress in the upscaled beam due to the weight.

$\sigma_{2,cen}$: Stress in the upscaled beam due to the centrifugal force.

$\sigma_{2,aer}$: Stress in the upscaled beam due to the flapwise aerodynamic force.

ω_2 : Rotational speed of the upscaled blade.

4. The aerodynamic loads acting on the reference and the upscaled blade are obtained independently from simulations in the aeroelastic code. The coefficient for the aerodynamic force in the flapwise direction is computed using the following equations:

$$C_{z,1}(x) = \frac{2F_{a,1}(x)}{\rho_a ((\omega_1 x)^2 + V^2) c(x)} \quad (12)$$

$$C_{z,2}(x) = \frac{2F_{a,2}(bx)}{\rho_a ((\omega_2 xb)^2 + V^2) c(bx)} \quad (13)$$

Where:

$C_{z,1}$: Coefficient for the aerodynamic force in the reference blade.

$C_{z,2}$: Coefficient for the aerodynamic force in the upscaled blade.

$F_{a,1}$: Aerodynamic force in the flapwise direction acting on the reference blade

$F_{a,2}$: Aerodynamic force in the flapwise direction acting on the upscaled blade.

5. The expressions for the maximum stresses acting on the blade for the reference and upscaled blade are obtained by addition of the stresses due to the weight, aerodynamics forces and centrifugal forces. The expression for the total stress is:

$$\sigma_{1,t}(x) = \sigma_{1,w} + \sigma_{1,cen} + \sigma_{1,aer} \quad (14)$$

$$\sigma_{2,t}(f(x), x) = \sigma_{2,w} + \sigma_{2,cen} + \sigma_{2,aer} \quad (15)$$

Where:

$\sigma_{1,t}$: Total stress in the reference blade.

$\sigma_{2,t}$: Total stress in the upscaled blade.

6. A ratio between the stress in the upscaled and the reference beam is defined as h .

$$h(f(x), x) = \frac{\sigma_{2,t}(f(x), x)}{\sigma_{1,t}(x)} \quad (16)$$

The expression for the stress ratio given in equation (16) is a constraint with a value of one, to have the same stresses in both blades. Thus an implicit equation is obtained for the non-linear function f .

$$h(f(x), x) = 1 \quad (17)$$

7. The chain rule is applied to equation (16). Also using equation (17), it is possible to find an explicit formula for f .

$$\frac{df}{dx}(x) = - \left(\frac{\partial h}{\partial f}(f) \right)_x^{-1} \cdot \left(\frac{\partial h}{\partial x}(x) \right)_f \quad (18)$$

Equation (18) is an integro-differential equation for f because it contains both derivative and integral terms. This equation is solved numerically to find the solution of $f(x)$.

3. Implementation: Upscaling the blades of the 5MW NREL wind turbine to a blades for a 20 MW machine

The non-linear upscaling method is applied on the blade of the 5MW wind turbine. The same tip speed for both blades is assumed, however the method does not have any constraint on selecting a different value at different scales. Thus the rotational speed of the upscaled blade is obtained by dividing the rotational speed of the reference blade by the linear upscaling ratio b .

The critical operational point for the reference blade is found at a wind speed of 12 m/s and a rotor speed of 12.1 rpm.

The method is programmed in MATLAB and linked with the aeroelastic code HAWC2 to predict the aerodynamic loads on the blades [6, 7].

The MATLAB code is automated to run aeroelastic simulations in HAWC2 for the upscaled and reference blade, and extract the aerodynamic loads from the simulations. The integro-differential equation mentioned in step 7 of the methodology is solved iteratively by adapting the numerical shooting method for solving ordinary differential equation.

The algorithm computes the loads acting on the new shape of the upscaled wind turbine in every iteration and takes into account the non-linear effects on the aerodynamic forces due to the changes in size and geometry of the upscaled blade.

4. Results of the 5MW upscaling

Figure 4 shows the ratio of the total stresses along both blades. As it can be seen, while the non-linear upscaling approach maintains the level of total stress

unchanged, the linear upscaled blade shows an increase of about 80% at the blade root.

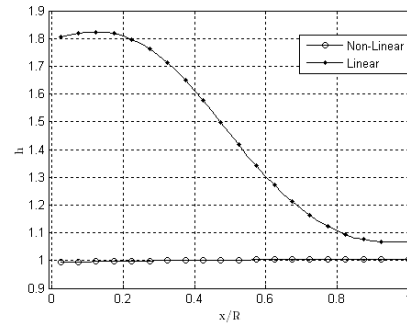


Figure 4: Linear and non-linear total stress distribution along the blade.

For the non-linear upscaled blade, the centrifugal stress is almost the same as the linear blade. However, the aerodynamics and weight stress distributions change.

Figures 5 and 6 show the ratio of different types of stresses in the reference and the upscaled blade respectively, with respect to the total stresses along the reference blade.

In figure 7 the values of the non linear function which maintains the stresses in the upscaled blade is shown. The values of the non-linear function are higher than one to maintain the stresses the same, especially in the area close to the root of the blade where the influence of the moment produced by the weight is higher.

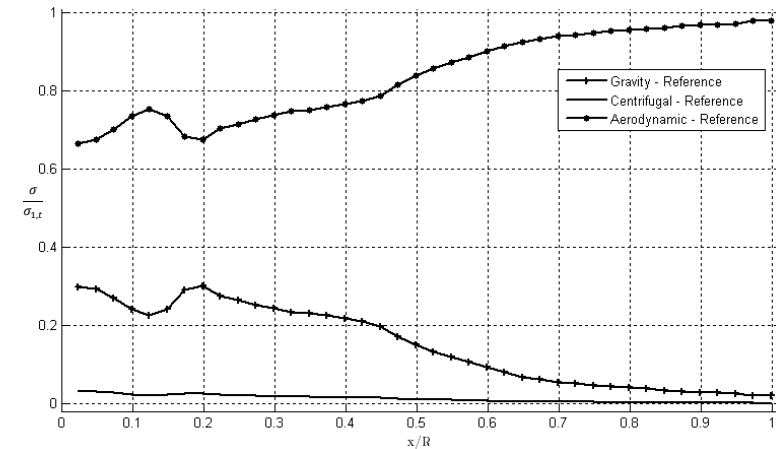


Figure 5: Distribution of different stresses over the reference blade.

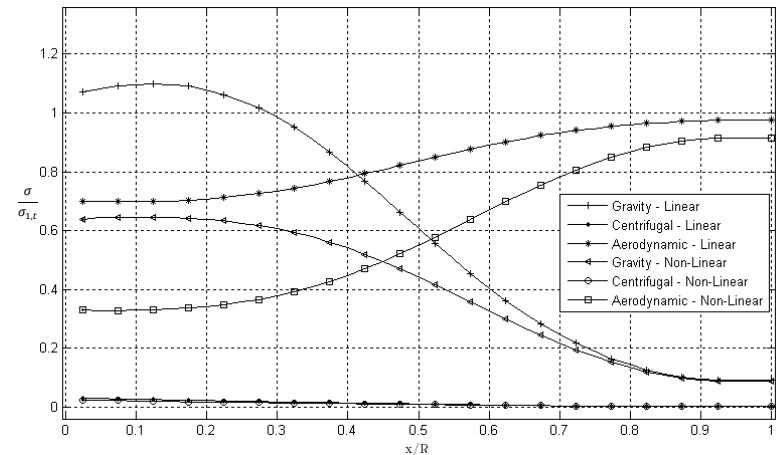


Figure 6: Distribution of different stresses over the upscaled blade.

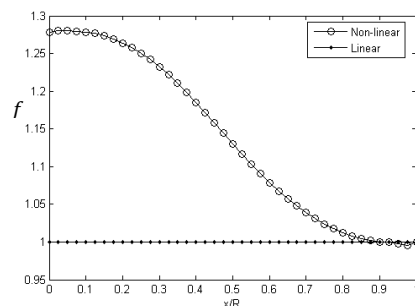


Figure 7: Values of the non-linear function for the 20MW blade.

Using the structural properties of the equivalent beam the mass of the blade is calculated and presented in table 1.

Wind turbine Blades	Mass [kg]
5MW reference	17743
20MW linear upscaled	141950
20MW non linear upscaled	217381

Table 1: Mass of the blades obtained from the equivalent beam properties.

The mass of the 5 MW blade is 17740 kg, which is almost the same value obtained using the equivalent beam properties as shown in table 1.

The 20 MW linearly upscaled blade is lighter than the nonlinear. This is because the solution of the equation (18) gives higher values of the material thicknesses to maintain the same level of stresses.

5. Conclusions

The non-linear upscaling method presented in this work obtains a blade that maintains the same level of stresses as the reference one. When the linear scaling law was used for the blade, an increase in the total stress of 80% occurs, which makes it a non-feasible design.

Non-linear upscaling decreases the aerodynamics stresses and weight induced stresses compared to a linear upscaling, while the centrifugal stresses are almost the

same in the linearly upscaled and the non-linear upscaled blade.

The stress caused by the weight is dominant close to the blade root and the stress caused by the aerodynamic forces is dominant in the blade tip region in both upscaling approaches.

The flapwise aerodynamic force obtained from HAWC2 is different in the linear and the non-linear 20 MW blade. This is due to the fact that the aerodynamic loads on the linear and non-linear blades are calculated with different angular and axial induction factors caused by a difference in flexibility in both flapwise and edgewise directions.

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