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Location-Optimized Aerodynamic Rotor Design of Small Wind Turbines and Lightweight Implementation Using Additive Hybrid Material

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Wind power plays a crucial role in supplying cities with renewable energy. Combined with short transport routes, it is essential to establish site-specific small wind turbines in the urban environment. An increasing interest in small, decentralized, vertical-axis wind turbines (VAWT) can be observed here. However, concepts with low visual and auditory effects and economic efficiencies are largely limited. The project part described in this paper enables a specially developed design software tool of rotor geometries optimized for such boundary conditions. By using fiber-reinforced structures in combination with selective laser sintering, it is theoretically possible to economically produce even the smallest quantities of these geometries for a typical service life of wind turbines. The results presented and discussed in this work can serve as a basis for a subsequent feasibility study.

Keywords: small wind turbine, vertical axis, VAWT, additive manufacturing, hybrid design, laser sintering technology, fiber-reinforced composites (FRP).

1. Introduction

Given the innovative role of Vertical Axis Wind Turbine (VAWT) in the growing market of small energy conversion facilities, both now and in the future, engineers and designers seem to continue to be challenged. Although Albert Betz has already proven that the wind is capable of producing a maximum of 59.2% of its energy, this fact does not prevent from getting as close as possible to this maximum by increasing efficiency in the energy-converting system.

To improve design and manufacturing process of the VAWT a special development in house tool in combination with hybrid materials are used at University of Applied Sciences Saarbrücken (htw saar) to make optimum use of the site-specific conditions for potential VAWT locations.

2. Rotor design process

The first approach to analyze the flow field around a vertical axis wind turbine was developed by Templin (1974), who considered the rotor to be an actuator disk enclosed in a simple stream tube. The induced velocity through the swept volume of the turbine was assumed to be constant [1].

An extension of the blade-element momentum theory resulted in the Multiple Stream Tube (MST) model, introduced by Strickland (1975), who considered the swept volume of the turbine as a series of adjacent stream tubes [2]. Paraschivoiu (1981) proposed the Double Multiple Stream Tubes (DMST) model that divides a multiple stream tube systems into two actuator disks where the upwind and downwind components of the induced velocities are evaluated as a function of the blade position for each stream tube [4].

More advanced aerodynamic methods for modelling wind turbines are based on vortex theory (Nguyen, 1978) [3, 4]. Within this project, a MST model (VAWT_POWER) which has already been described by Müller et al. [5] is used. The VAWT_POWER program is distinguished by a special consideration of lift and resistance coefficients. These coefficients are Reynolds number dependent and can also be correctly considered for the evaluation for profiles depending on the locally prevailing conditions.

2.1. *Boundary condition*

The main turbine design parameters (tip-speed-ratio, rated power) were derived from typical wind speed measurements at an urban location as shown in Fig. 1 (*campus htw saar* Saarbücken, Germany). A cup anemometer with data logger function was used, which is installed on a measuring mast four meters above the building roof.

The wind speed and wind direction data were collected over a time period of one year (Oct. 14 – Oct. 15). Therefore, the measured data are then available as ten-minute averages. The frequency distribution of wind speed suggested a 'weak wind turbine'-design (larger rotor to reach the defined rated power).

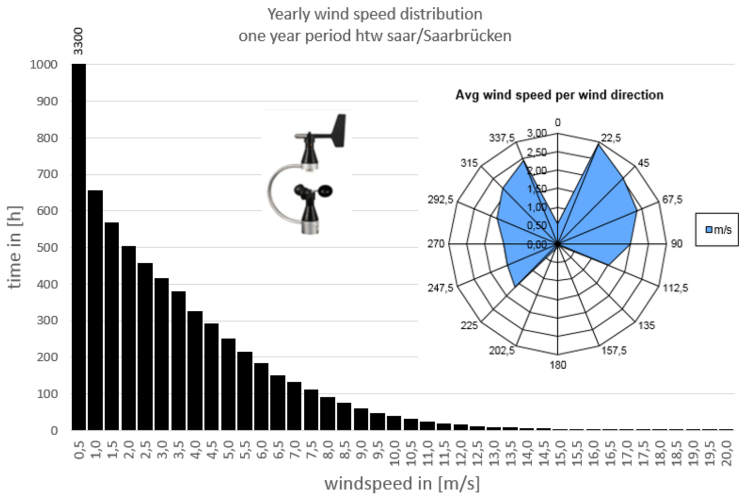

Figure 1 Results of wind speed and wind direction measurements over a one-year period at htw saar's Alt-Saarbrücken site

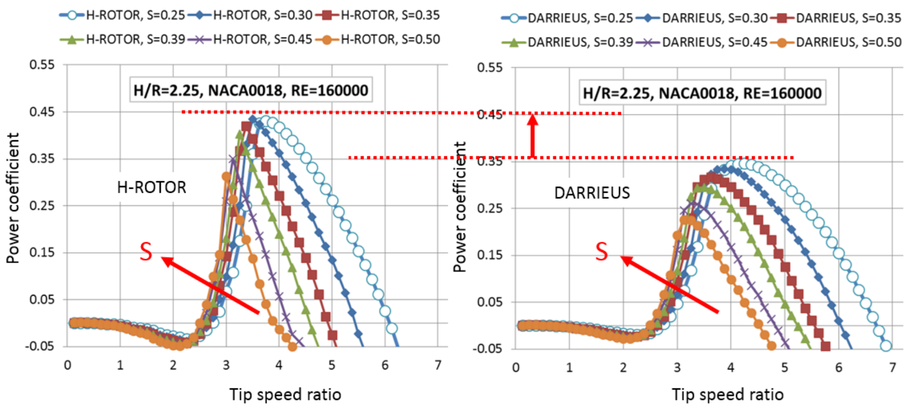

Figure 2 Comparison of power coefficient CP between Darrieus and H-rotor for growing solidities S

2.2. *Aerodynamic optimized rotor geometry*

Solidity (ratio of blade volume to rotor volume) is one main design parameter of the rotor, which has a strong impact on the turbine power curve and start up behavior. A run up parameter study with VAWT-POWER (constant chord length over the blade; rotor high to rotor diameter of 2.25) shows that the turbine power coefficient decreases with increasing solidity (S) values (Darrieus and H-Rotor). H-Rotors can also realize higher power coefficients (CP) than Darrieus rotors (for NACA0018-blades, CP = 0.35 for Darrieus; CP = 0.43 for H-Rotor) as shown in Fig. 2. The

used lift and drag coefficients (CL and CD) for calculation with VAWT_POWER, refer to characteristics of a two-dimensional airfoil section. The used coefficients are calculated out of wind tunnel experiments of a NACA0012 using a synthesizer code [5].
Calculations of power curves based on interpolation of Reynolds numbers dependent coefficients showed that a reduction of power coefficients at low tip-speed ratios is enormous (negative CP values, which indicate that the turbine needs external power to start up). This indicates the poor self-starting capability of the small VAWT [6].

2.3. *Force flow optimization*

A CAD-model was created and different operating conditions were calculated with Finite-Element-computations for selected user specified load cases, e.g. typical operation conditions (based on IEC 61400-2 DLC 1.1) and max. loads (based on IEC 61400-2 DLC 1.4) as showed in Fig. 3. The force flow or force distribution along the blade to the turning part of the generator is investigated based on the main principal stress path.

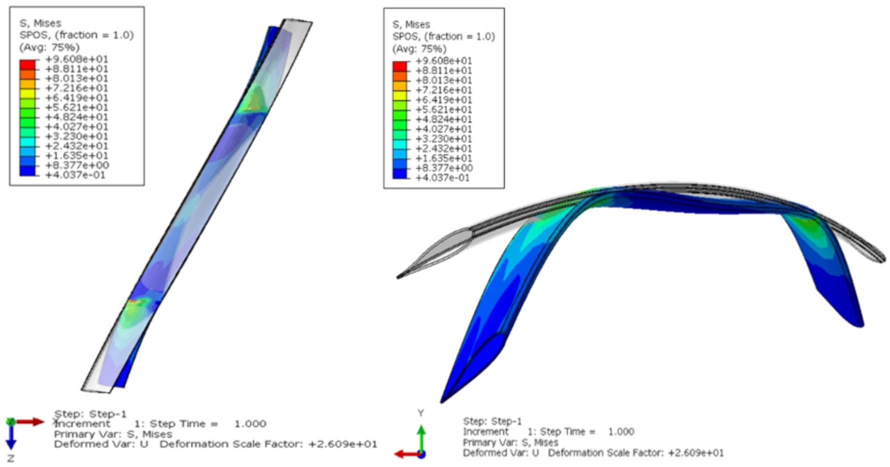

Figure 3 Stress distribution and deformation according to finite element analysis for defined load cases and hybrid material data

Based on experience reports it was taken into account that the connection points between blade and hub are a weak point in commercially available small VAWTs (up to 10 kW) next to vibration problems in tower and foundation structures who are not focused in this work. Due to the complex and strongly fluctuating superposition of forces acting span wise, flatwise and edgewise during one revolution, resulting load vectors on the sheet surface were determined using CFD simulation [7]. If these forces are used as boundary conditions for a finite element analysis, especially in the area of blade connection, increased stresses results from bending and torsion moments. Caused of the blade geometry, the bending stiffness in edgewise direction is lower than span wise as shown in Fig. 3. Due to this lower stiffness, the deformations in the edgewise direction are significantly increased, which leads to greater stresses in the component. To relieve the connection points and reduce these stress peaks, an additional degree of freedom is introduced. This allows the blade to deform in the longitudinal direction and thus reduces the maximum stresses at the connection point without reducing the rotor torque. In addition, the stress distribution along the blade is analyzed and force paths are derived.

3. Production process

After the rotor geometry has been designed, it must be implemented as accurately as possible to get the estimated aerodynamic behavior. This places high demands on the production process and on the materials, because the whole system should work without a failure over a longer time period (e.g. 20 years).

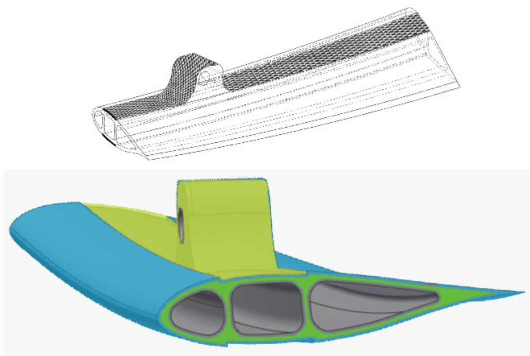

Figure 4 Lightweight and force flow optimized blade geometry

3.1. *Lightweight and force flow optimization*

Based on the FEA results and with regard to the manufacturing process of the rotor blades, the fibre orientation of the reinforced material is oriented along the load paths. The use of hybrid components offers the freedom to optimize this process. The aerodynamic free-form surface can be produced without restrictions using additive production methods. In addition, wall thicknesses can be varied as required. In order to make the blade more rigid, structures are planned which lead to individual chambers within the profile. In addition to simple strut structures, bionic structures can also be used for lightweight construction and material efficiency. A possible approach here is, for example, the internal structure of a bone. The investigation of suitable structures is a current research topic of Häfele et al. [9].
The load paths are taken into account and mapped using groove structures as could be seen in Fig. 4. The alignment of the connection points can be clearly defined and optimally integrated into the load path.

3.2. *Additive hybrid process*

These hybrid components are based on core structures with optimized geometry, manufactured by selective laser sintering (SLS), which serve as base for the cladding with fiber-reinforced composites (FRP). Finally, they get finished by Vacuum Assisted Resin Infusion (VARI) to complete the fiber reinforcement as described from Häfele et al. [9].
The objective of this approach is the production of SLS/FRP-hybrid components with complex structures, regarding high-strength, multi-functionality as a well as material efficiency. In this context, the process-typical anisotropic properties, e.g. tensile strength or surface quality have to be considered in the design process.
The materials used are PA2200, based on polyamide 12 and carbon fibers (rovings, layers, and weavings) as well as thermosetting/thermoplastic matrix systems. In spite of the wide range of thermosetting resins and the appropriate fiber types, the thermoplastic matrix has an improved connection and processing characteristic. For example, the cycle time of VARI can be reduced from 24h (thermosetting resin) to 45 min (thermoplastic resin). In addition, the thermoplastic matrix can be reshaped under the influence of heat and allows the recycling of SLS/FRP-Hybrids.

4. Measurement

After the production of the rotor blades and the drive train, the prototype can be assembled and tested. To check the rotor blade and the manufacturing process, Häfele et al. [9] first tested the mechanical properties [9]. Essential results of this work are listed here once more. This was necessary to reduce or exclude a failure for subsequent tests in the wind tunnel.

4.1. *Mechanical properties*

Exemplarily a rotor blade module has been reinforced with carbon fibers to compare the bending strength of SLS and SLS/FRP-hybrid parts. Thus, the reinforcement increases the bending strength up to 500%, with an increasing of only 20%. This process and experimental investigation was described from Häfele et al. [9].

Table 1 Approaches for different materials

Approach	AM – SLS	Hybrid – SLS/FRP	Gain factor
Deflection	3 mm	0.69 mm	0.23
	6 mm	1.21 mm	0.20
Mass	94 g	113 g	1.2

4.2. *Aerodynamical properties*

In order to compare simulations (Ruffino et al. [8]) and investigate turbines behavior more deeply, a wind tunnel is used (see Fig. 5). The so-called Göttinger design circulates air inside in a closed setup. Dimensions of the tunnel are 12 m x 3.5 m x 2m. Air is driven by a 75 kW rotor placed on upper side.

The nozzle diameter is about 1.6 x 1.6 meter for the test section setup. The VAWT can be placed in this position. Access points are positioned for temperature, pressure and velocity flow examinations. An additional heat absorber is used to control the air temperature to ensure comparable environmental conditions during the tests.

Figure 5 Low speed wind tunnel with test-rig and installed VAWT prototype

Due to the small rotor diameter of 1 m and the very short chord length of the blades (75 mm) for this diameter, problems arise when starting up the system. These result on the one hand from the blocking effect (39%) due to the plant size and the measuring distance, which is why corrections must be made when evaluating the measurement results, e.g. after Ryi et al. [10]. Based on these corrections, the volume flow rate must be increased in order to obtain a comparable behavior of the system without blockage. In terms of quality, however, the behavior of the system with and without blocking is similar. For this reason, the starting behavior of the prototype was measured at different wind speeds.

First, the CFD simulations of Ruffino et al. are used to validate the VAWT_POWER results. The result is that the qualitative course of the curves is the same. Fig. 6 shows the results of the VAWT_POWER-Tool for different wind speeds. A variation of the inflow velocity between 3m/s and 10m/s clearly shows that the system starts up but does not accelerate further into the actual operating range due to the negative cp-TSR curve.

To check this behavior, the same inflow velocities are set in the wind tunnel. The results of the experiment support the simulation and calculation results. The system starts up and reaches a stable operating point at very low speed. As expected, there is no further acceleration even when wind speeds are increased and is marked accordingly in Fig. 6.

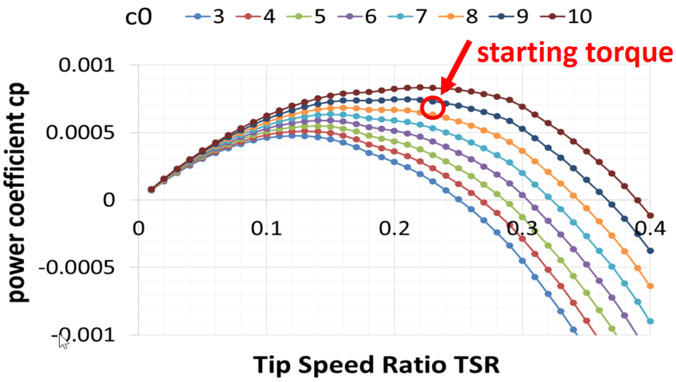

Figure 6 Details of the results of the mathematical model for starting process of a small-scale vertical axis wind turbine (VAWT) with power coefficient over tip speed ratio; critical starting torque can be identified

5. Conclusions

Starting with wind speed and direction measurements, the boundary conditions for the given location are determined. With help of the VAWT_POWER-Tool, an aerodynamic optimized rotor design can be designed. The existing wind conditions are optimally used by adapting various parameters. Afterwards this weak wind rotor is recalculated with finite element methods. The main load paths are determined by specifying representative load cases.

An additive hybrid material is used to implement the geometry. The defined load paths can be mapped by grooves in the additive production core. In order to transfer the loads to the drive train, carbon-fiber-reinforced composite materials are used. This combination of SLS and VARI provides additional freedom in terms of lightweight construction and in the geometric design of the connection points. This makes it possible to introduce degrees of rotational freedom in order to reduce the loads in the connection points and thus in the drive train. Subsequent mechanical experiments show significantly improved mechanical properties, e.g. with regard to deflection (up to 500%) with a slight increase in mass (plus 20%). This means that material can be used significantly more efficiently in terms of resources. Subsequent performance tests in the wind tunnel confirm the design results of the implemented prototype.

With the help of the CFD simulation results and the experimental investigations, the VAWT_POWER results could be qualitatively validated. For the full validation of the VAWT_POWER-Tool, losses caused of the drivetrain must be considered. In addition, the measured results form the wind tunnel must be corrected by blockage effects. In addition, it must be checked whether the approach of Ryi et al. [10] can also be used for VAWTs, since VAWTs cannot be calculated in a simplified way with a rotor disk as it is used for horizontal axis wind turbines.

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