Ain Shams University

Faculty of Engineering

Design and Production Engineering Department

# Structural Optimization of Horizontal Axis Wind Turbine Blades

A Thesis Submitted in Partial Fulfillment for the Requirements of the Degree of Master of Science in Mechanical Engineering

by


**Julia Raafat Faheem Ramzy Faheem Petro**

Bachelor of Science in Mechanical Engineering

Design and Production Engineering

Faculty of Engineering, Ain Shams University, June 2012


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Cairo - (2018)

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# Statement

This thesis is submitted in partial fulfillment for the degree of Master of Science in Mechanical Engineering, to Faculty of Engineering, Ain Shams University. The author carried out the work included in this thesis at the laboratories of the Design and Production Engineering department, Faculty of Engineering, Ain Shams University. No part of this thesis has been submitted for a degree or qualification at any other university.

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# *Researcher Data*

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# *Thesis Summary*

Designers of modern wind turbines are more interested in stiffer and lighter blade designs as the growth of their size leads to reducing the production costs of electrical energy. The present work introduces a design analysis framework for wind turbines, using a combination of tools specially developed for this purpose. SNL 100-00 is taken as a reference wind turbine blade originally designed by Sandia National Labs. This blade is chosen as a case study to implement the proposed methodology. The first step in the methodology is to model the blade structure using two pre-processing python scripts: (1) Airfoil2BECAS to create a 2D finite element shell model for each cross-section and (2) Shellexpander to generate the input files which are needed by the cross-sectional analysis software BECAS. The cross-sectional properties of the glass fiber-epoxy composite wind turbine blade computed by BECAS are then used as input to the aeroelastic code HAWC2 to conduct aeroelastic analysis and simulate DLCs where HAWCStab2 is used for tuning the controller parameters. The results developed by the proposed methodology are validated against those published by Sandia National Laboratories. Close agreement is observed and hence the proposed methodology can be used to introduce design modifications to improve the blades characteristics. Modifications including (1) changing the slope of the shear webs and (2) the spacing between them are investigated showing good chance of improving the structural and inertial properties of the blade. To evaluate such modifications, comparison against baseline design is conducted using the following metrics: Flapwise and Edgwise loading, tip deflection and cross-sectional properties including: Flapwise and Egdewise bending stiffnesses, axial stiffness, torsional stiffness and mass density.

PSO algorithm is utilized to develop an automatic tool to design optimal structure of wind turbine blades. The developed code is used to solve a benchmark problem and results are validated against published results and also against results obtained using GA toolbox in MATLAB. Finally, the optimization code is combined with the blade's analysis framework presented to find the optimal slope for the shear webs and the optimal spacing distribution. Three variants of the objective function are considered aiming to reduce the mass and increase the stiffness of the blade. The resulting optimized configuration increases the flapwise stiffness normalized by mass density by varying percentages along the span of the blade reaching up to 18% increase and life expectancy increase ranging between 10-75%. This increase is expected to be directly reflected on the blades cost.

**Keywords:** Structural Optimization, Wind turbine blades, Cross sectional analysis, Finite Element Modeling, Composite structures, Aeroelastic analysis.

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Cairo, December 2018
Julia Petro

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# List of Abbreviations

| | |
|---|---|
| HAWT | Horizontal Axis Wind Turbine |
| COE | Cost of Energy |
| FEM | Finite Element Modeling |
| BEM | Blade Element Momentum theory |
| IEC | International Electro-technical Commission |
| DLC | Design Loading Case |
| NUMAD | Numerical Manufacturing And Design tool |
| FAST | Fatigue, Aerodynamic, Structures and Turbulence |
| BECAS | Beam Cross section Analysis Software |
| VABS | Variational Asymptotic Beam Section Analysis |
| HAWC2 | Horizontal Axis Wind turbine Code 2 |
| PSO | Particle Swarm Optimization |
| GA | Genetic Algorithm |
| MMA | Method of Moving Asymptotes |
| GBA | Gradient Based Approach |
| EA | Evolutionary Algorithms |
| MPI | Message Passing Interface |

# List of symbols

| | |
|---|---|
| $V(z)$ | Wind velocity profile |
| $V_{hub}$ | Wind velocity at the hub height |
| $z_{hub}$ | Height of the hub measured from the ground |
| $\alpha$ | Wind shear power law exponent |
| $\sigma_t$ | Turbulence longitudinal standard deviation |
| $I_{ref}$ | Expected value of hub-height turbulence intensity at a 10 min. average wind speed of 15 m/s |
| $V_{ave.}$ | Mean value of the wind speed |
| $V_{ref.}$ | Reference wind speed average over 10 min |
| $T$ | Rise time |
| $\theta_{cg}$ | Direction change |
| $V_{gust}$ | Velocity of gust wind |
| $D$ | Rotor diameter |
| $\Lambda_1$ | Turbulence scale parameter |
| $\theta_e$ | Extreme direction magnitude |
| $V_{e50}$ | Extreme wind speed with a recurrence period of 50 years |
| $V_{e1}$ | Extreme wind speed with a recurrence period of 1 years |

| | |
|---|---|
| $\boldsymbol{d}$ | Fraction of chord length increase at the section closest to the root |
| $\boldsymbol{S}$ | Slope of shear webs spacing linear distribution function |
| ***stel*** | Short term equivalent load |
| $\boldsymbol{m}$ | Wöhler slope |
| $\boldsymbol{N_{eq}}$ | Length of simulation in seconds |
| ***NeqL*** | Lifetime equivalent load number |
| $\boldsymbol{f_0}(\mathbf{x})$ | Fitness function |
| $\boldsymbol{x_j}$ | Design variable *j* |
| $\boldsymbol{x_j^L}$ | Lower bound of design variable $x_j$ |
| $\boldsymbol{x_j^U}$ | Upper bound of design variable $x_j$ |
| ***pbest*** | A particle's personal best experience |
| ***gbest*** | Global best, the best fitness achieved in an iteration |
| $\boldsymbol{v_i^k}$ | Particle velocity in the $k^{th}$ iteration |
| $\boldsymbol{x_i^k}$ | Particle position in the $k^{th}$ iteration |
| $\boldsymbol{w}$ | Inertial weight of a particle's previously attained position |
| $\boldsymbol{c_1}$ | Cognitive constriction coefficient |
| $\boldsymbol{c_2}$ | Social constriction coefficient |

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