



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

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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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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 Edgewise loading, tip deflection and cross-sectional properties including: Flapwise and Edgewise 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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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
α	Wind shear power law exponent
σ_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
θ_{cg}	Direction change
V_{gust}	Velocity of gust wind
D	Rotor diameter
Λ_1	Turbulence scale parameter
θ_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

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

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