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Multi-objective material selection for wind turbine blade and tower: Ashby's approach

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ABSTRACT

The world today is continuously striving towards carbon neutral clean energy technology. Hence, renewable energy sources like wind power system is increasingly receiving the attention of mankind. Energy production is now no more the sole criterion to be considered when installing new megawatt (MW) range of turbines. Rather some important design parameters like structural rigidity, cost effectiveness, life cycle impact, and, above all, reduced mass come into the scenario from new installation point of view. Accordingly, these issues are followed up in this article from wind turbine design perspective. The study, at the outset, aims to establish blade and tower material selection indices on the basis of inherent structural constraints and potential design objectives. Next, it highlights entire blade and tower material selection aspects for small and large scale horizontal axis wind turbines, both for onshore and offshore application. Finally, it distinguishes advanced blade and tower materials in agreement with multiple constraint, compound objective based design optimization procedure. Findings from the study can be deployed to harness massive scale wind energy from structurally more promising, economically more competitive and environmentally more clean and green turbines.

1. Introduction

Wind power industry is experiencing a spectacular growth in recent days. With government thrust and deployment of latest technological know-how, new megawatt (MW) range of turbines (specially offshore ones) have eventually been evolved that are even larger than latest largest aircrafts. Extended plans have henceforth been envisaged to design 20 MW wind turbine along with extreme strength to mass ratio, high degree of reliability, and overall mass reduction [1]. Apart from mass and structural optimization, cost curtailment, embodied energy diminution and carbon footprint minimization are substantially important parameters for new generation design of such massive structures. More recently, the design space has also been expanded abundantly due to increasing number of materials. A plethora of new materials has been discovered by research community that implies further competitive design to such industries. Well-known estimates now count the number of engineering materials far more than 80,000. Many traditional materials that once ran the wheels of industrial revolution have, thus far, been thrivingly replaced with more suitable, superior quality material families. Wind turbine industry has, simultaneously, deployed better quality alloys, composite materials and sandwich structures in the past decade. Though these materials are meeting today's industry demand, there is still ample opportunity to optimize future large scale onshore and offshore wind turbine material selection process as green and recyclable composite, sandwich materials are increasingly entering the market [2] and their per unit cost is steadily declining thanks to advanced manufacturing and process technologies. Further to that, price of the traditional ones is rapidly escalating simultaneously due to inflationary onslaughts. Hence, a renewed interest in wind turbine material selection process is burgeoning in this concourse. Besides, several life cycle analysis (LCA) techniques have also been evolved lately that can evaluate cradle to grave inventory and impact assessment of an entire stand-in technology. These LCA techniques lead to environmentally more sensible design at the time when green house gas (GHG) emission, global warming and UN Intergovernmental Panel on Climate Change (IPCC) issues have notably appeared as fervent topics of the hour. Though wind power, being one of the most ubiquitous and unpolluted, in-exhaustible and sustainable energy on planet earth, contributes very little to the surrounding environment during its operation phase, the base material production processes extensively affect the environment due to enormous size. Such grim realities ultimately propel to more environmental conscious material selection for tomorrow's wind turbines with more clean and green outlook. Additionally, commercial scale wind farm development has already expanded to over 80 countries with 175 GW rated capacity while some European countries like Denmark is now planning to meet at least 50% of its electricity demand

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Nomenclature

ρ_a	density of air (kg/m^3)
ρ	density of material (kg/m^3)
Ω	blade rotational speed (rpm)
σ_f	fatigue strength of material (MPa)
σ_{flap}	flapwise bending stress (MPa)
σ_{shell}	edgewise bending stress (MPa)
A_2	rotor swept area (m^2)
C	distance between top and neutral surface (m)
C_C	coupling constant
C_{CO}	cost per unit weight (USD/kg)
C_{CO_2}	carbon footprint per unit weight (carbon footprint/kg)
C_{EE}	embodied energy per unit weight (embodied energy/kg)
D	tower mean outer diameter (m)
D_{bottom}	tower bottom outer diameter (m)
D_{top}	tower top outer diameter (m)
$\dot{E}_{extracted}$	extracted power from rotor (W/s)
F	aerodynamic force on rotor (N)
I	area moment of inertia (m^4)
K_{IC}	fracture toughness (MPa $\sqrt{}$m)
L	tower length (m)
M_{flap}	blade flapwise bending moment (N m)
M_{edge}	blade edgewise bending moment (N m)
M_{bend}	bending moment at tower base (N m)
MI	material index
P	buckling load on tower (N)
R	blade radius (m)
T	rotor thrust (N)
V_1	free stream wind velocity (m/s)
V_2	wind velocity through rotor (m/s)
c	average chord length (m)
d	average chord width (m)
m_{blade}	blade mass (kg)
m_{spar}	spar mass (kg)
m_{shell}	shell mass (kg)
m_{tower}	tower mass (kg)
$\dot{m}$	wind mass flow rate (kg/s)
r	radial distance from rotor axis to blade element (m)
$t/2$	blade shell thickness (m)
t	tower mean wall thickness (m)
w_i	weight factor percentage

from wind power by 2025 [3]. As worldwide electricity demand is doubling itself in every 10 years, the contribution of wind power will also continue to surge simultaneously. Hence, a through exercise on wind turbine material selection process is sine-qua-non that will help explore new materials that can withstand wind turbine structural demands with even competitive mass, price and environmental impact than the currently used ones.

2. Material selection principle for horizontal axis wind turbine

Over a design life of 20 years, wind turbine endures highly turbulent aerodynamic load and numerous fatigue producing stress cycles. A large turbine in its 30–70 rpm revolution usually experiences 10^8–10^9 cycles over its lifetime with an annual 4000 h operation [4]. This may be compared to many other manufactured items that would be unlikely to experience more than 10^6 cycles over their entire lifecycle. On top of the aerodynamic loading, there is significant gravitational, centrifugal, gyroscopic, inertia, and brake loads. Interaction of these loadings together with blade aerodynamic profile makes the real-time load scenario very complex. Designing such an aerodynamic structure simultaneously for decreased mass, cost, environmental impact and embodied energy obviously leads to a multiple constraint and compound objective based optimization problem.

Within the last decades, different material selection and optimization procedures have been explored in design community. Out of these, Zhu et al. [5] proposed a knowledge-based design support system (KDSS) for optimal material selection of energy absorbers based on axiomatic design principle [6], embodying three functional requirements (so called 'what we want to achieve' factors) with corresponding, relevant design solutions ('how to achieve' factors). A purpose-built software, Swinburne Energy Absorber Design Supporter (SEADS), is used in this confluence to demonstrate the procedural material selection aspects. The functional requirements include knowledge based optimal design search destined for searching and ranking the materials, knowledge-based optimal design calculation that influences the selection if appropriate data are unavailable and concurrent 'supporting knowledge demonstration' process in the form of user guide, video and/or failure analysis which guides the entire decision compromise paradigm.

In another article, Waterman et al. [7] evaluated various existing computerized material data and information systems in pursuit of further rationalizing and streamlining the concomitant objectives and requirements of the materials and design engineers. Accordingly, Sapuan [8] highlighted the genuine importance of computer aided material selection systems with added emphasis on diverse knowledge base material selection procedures with their individual voluntary selection spaces (e.g. composite, plastic or entire material genre like cambridge engineering selector (CES) database). Distinct knowledge sharing patterns are explained in addition to a concurrent analysis on how knowledge based system (KBS) contributes towards advanced material selection methods, product design and its subsequent modification, development. Apart from a commentary on companion software packages, composite material based KBS systems drew enhanced attention due to their ever-increasing usage in today's design realm. In turn, Sirisalee et al. [9] focused on multi-objective optimization which is hinged on utility function approach with trade-off surfaces and its attributive Pareto front, dominated solution and no-dominated solutions. The trade-off surfaces and their tangential material contours offer the best compromising solutions between different conflicting objectives, a recurrent manifestation in design problems. The study demonstrated one disk brake caliper and another mini disk player casing material selection strategy based on conflicting objectives which provide sound representation of the trade-off surfaces only for maximum three objectives though the same utility function approach can be addressed for any number of objectives analytically.

However, a list of these different material screening tools can be categorized in five major sub-classes, viz., artificial intelligence based method, cost per unit property method, questionnaire based method, materials in products selection (MiPS) tools and index and chart based methods [10,11]. Out of these, index and chart based method and, more specifically, the Ashby material selection approach is applied in this discourse to explore optimal wind turbine blade and tower material selection. Ashby approach, in essence, first translates the design necessities into some performance objectives. Then, it screens out the unsuitable materials; surviving materials are, henceforward, ranked out to get the best materials according to the desired objective [12,13]. Objectives are basically aims or targets that are achieved throughout the design exercise. The minimum or maximum levels of property values, to which these