Design Analysis of Fixed-pitch Straight-bladed Vertical Axis Wind Turbines with an Alternative Material

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ABSTRACT

Fixed-pitch straight-bladed vertical axis wind turbine (SB-VAWT) is one of the simplest types of turbomachines which are mechanically uncomplicated. One of the most important design parameters for cost-effective SB-VAWT is selection of blade material. SB-VAWT blades must be produced at moderate cost for the resulting energy to be competitive in price and the blade should last during the predicted lift-time (usually between 20 and 30 years). At present, Aluminium blades fabricated by extrusion and bending are the most common type of VAWT materials. The major problem with Aluminium alloy for wind turbine application is its poor fatigue properties and its allowable stress levels in dynamic application decrease quite markedly at increasing numbers of cyclic stress applications. Under this backdrop, an attempt has been made in this paper to investigate alternative materials as SB-VAWT blade material. In this paper, required properties of the SB-VAWT Blade Materials are first identified. Then available prospective materials are shortlisted and assessed. Subsequently, comparisons are made between the available materials based on their mechanical properties and costs. Then, the most attractive alternative material is selected for detail design analysis using an analytical tool. Finally, comparisons have been made between the design features of a SB-VAWT with Aluminum and the alternative material blades using one of the prospective airfoils. The results of the design analyses demonstrates the superiority of the alternative blade material over conventionally used Aluminum.

Nomenclature

A	projected frontal area of turbine
c	blade chord
C_P	turbine overall power coefficient = $P_o / ½\rho AV_\infty^3$
C_{Pd}	design power coefficient
H	height of turbine
HAWT	Horizontal Axis Wind Turbine
m_b	mass of blade per unit blade height
N	number of blade
P_o	overall power output
R	turbine radius
S_a	allowable stresses
SB-VAWT	straight-bladed vertical axis wind turbine
t_s	blade skin thickness
$V_{cut-out}$	cut-out wind speed
$V_{\infty d}$	design wind speed
VAWT	vertical axis wind turbine
λ_d	design tip speed ratio
μ	aspect ratio = H / c
σ	solidity = Nc/R
ω_d	design angular velocity of turbine
γ_d	pitching of blade

1. Introduction

Fixed-pitch straight-bladed vertical axis wind turbine (SB-VAWT) is one of the simplest types of turbomachines which are mechanically uncomplicated. As shown in Figure 1, fixed-pitch SB-VAWT has only three major physical components, namely (a) blade; (b) supporting strut; and (c) central column. One of the most important design parameters for cost-effective SB-VAWT is selection of blade material. SB-VAWT blades must be produced at moderate cost for the resulting energy to be competitive in price and the blade should last during the predicted lift-time (usually between 20 and 30 years).

Though horizontal axis wind turbines (HAWTs) work well in rural settings with steady uni-directional winds, SB-VAWTs have numerous advantages over them. Unlike HAWTs, fixed-pitch SB-VAWTs are mechanically simpler and they do not require additional components (like yaw mechanics, pitch control mechanism, wind-direction sensing device). Furthermore, almost all of the components requiring maintenance are located at the ground level, facilitating the maintenance work appreciably. The maintenance cost is minimal with SB-VAWT in comparison to diesel gensets typically used as a backup or off-grid power source.

At present, Aluminium blades fabricated by extrusion and bending are the most common type of VAWT materials. The major problem with Aluminium alloy for wind turbine application is its poor fatigue properties and its allowable stress levels in dynamic application decrease quite markedly at increasing numbers of cyclic stress applications. Under this backdrop, an attempt has been made in this paper to investigate alternative materials as SB-VAWT blade material.

2. Required Properties of the Blade Materials

SB-VAWT blades are exposed to diversified load conditions and dynamic stresses are considerably more severe than many mechanical applications. Based on the operational parameters and the surrounding conditions of a typical SB-VAWT for delivering electrical or mechanical energy, the following properties of the SB-VAWT blade materials are required [1]:

- It should have adequately high yield strength for longer life;
- It must endure a very large number of fatigue cycles during their service lifetime to reduce material degradation;
- It should have high material stiffness to maintain optimal aerodynamic performance;
- It should have low density for reduced amount of gravity and normal force component;
- It should be corrosion resistant;
- It should be suitable for cheaper fabrication methods;
- It must be efficiently manufactured into their final form; and
- It should provide a long-term mechanical performance per unit cost;

Among all these requirements, fatigue is the major problem facing both HAWTs and VAWTs and an operating turbine is exposed to many alternating stress cycles and can easily be exposed to more than 10^8 cycles during a 30 year life time [2]. The sources of alternating stresses are due to the dynamics of the wind turbine structure itself as well as periodic variations of input forces [2].

3. Prospective Materials

The smaller wind turbine blades are usually made of aluminum, or laminated wood [3]. Metals were initially a popular material because they yield a low-cost blade and can be manufactured with a high degree of reliability, however most metallic blades (like steel) proved to be relatively heavy which limits their application in commercial turbines [4]. In the past, laminated wood was also tried on early machines in 1977 [5]. At present, the most popular materials for design of different types of wind turbines are wood, aluminum and fiberglass composites that are briefly discussed below.

Wood and Wood Epoxy

Wood, a naturally occurring composite material, is readily available as an inexpensive blade material with good fatigue properties [2]. Wood has been a popular wind turbine blade material since ancient time. Wood has relatively high strength-to-weight ratio, good stiffness and high resilience [4]. Wood and wood epoxy blades have been used extensively by the designer of small and medium sized HAWTs. However, wood does have an inherent problem with moisture stability. This problem can be controlled with good design procedures and quality controlled manufacturing processes. The application of wood to large blades is hindered by its joining efficiency which in many cases has forced designers to examine other materials [4].

Aluminum

Aluminum blades fabricated by extrusion and bending are the most common type of VAWT materials. The early blades of Darrieus type VAWTs were made from stretches and formed steel sheets or from helicopter like combinations of aluminum alloy extrusions and fiberglass [6]. It has been reported by Parashivoiu [6] that the former were difficult to shape into smooth airfoil, while the latter were expensive. The major problem that aluminum alloy for wind turbine application is its poor fatigue properties and its allowable stress levels in dynamic application decreases quite markedly at increasing numbers of cyclic stress applications when compared to other materials such as steel, wood or fiberglass reinforced plastics [2].

Fibreglass Composites

Composites constructed with fibreglass reinforcements are currently the blade materials of choice for wind turbine blades [4] of HAWT types. This class of materials is called fibreglass composites or fibre reinforced plastics (FRP). In turbine designs they are usually composed of E-glass in a polyester, vinyl ester or epoxy matrix and blades are typically produced using hand-layup techniques. Recent advances in resin transfer moulding and pultrusion technology have provided the blade manufacturers to examine new procedures for increasing the quality of the final product and reducing manufacturing costs [4]. The characteristics that make composites, especially glass fiber-reinforced and wood/epoxy composites, suitable for wind turbine blades are [7]:

- low density;
- good mechanical properties;
- excellent corrosion resistance;
- tailorability of material properties; and
- versatility of fabrication methods.

According to Sutherland [4] – *“The most significant advancement over this decade is the development of an extensive database for fibreglass composite materials. This database not only provides the designer with basic material properties, it provides guidance into engineering the material to achieve better performance without significantly increasing costs. Some questions have yet to be answered, but research is ongoing. The primary ones are the effects of spectral loading on fatigue behaviour, scaling the properties of non-metallic materials from coupons to actual structures, and environmental degradation of typical blade materials.”*

4. Comparative Analysis between Available Materials

It has been found from literature survey that in recent times both fiberglass-reinforced and wood/epoxy composites have been shown to have the combination of strength and low material and fabrication costs required for competitive blade manufacture [7].

Precise control of airfoil geometry is quite important in providing blades with consistent aerodynamic properties and small variations in outboard airfoil camber (±1/4 percent of chord) can lead to substantial aerodynamic imbalance and rotor and turbine life reduction [7]. This need for aerodynamic consistency and accuracy has led to the adoption of molding as the fabrication method of choice for both fiberglass and wood/epoxy composites, as it provides control right at the outer aerodynamic surface, which determines the ultimate performance. Both material systems are able to provide the complete range of outboard airfoil shapes currently of interest [7].

In mid nineties, a comprehensive investigation on alternative materials for use in medium-size VAWT blades was conducted by W. R. Davis Engineering Ltd for the CANMET Energy Technology Centre (CETC) of Canada [2]. It seems that the main focus of this study was curved-type VAWTs. However, significant insight regarding different blade materials can be understood from this study. In this study, consideration was given to parameters of aerodynamic performance, structural capabilities, corrosion, erosion and cost. Six types of blade materials, namely (i) aluminum; (ii) stainless steel; (iii) low carbon steel; (iv) titanium; (v) fibre reinforced composites; and (vi) wood and wood epoxy, were considered in the study. It was found that pultruded FRP is economically more viable than all the materials considered in the study. It was also been found that the mechanical strength (ultimate strength, fatigue strength) of the pultruded FRP is significantly better than commonly used Aluminum and comparatively it is lighter in weight. Some of the key findings related to the viability of pultruded FRP blades which came from the CETC [2] report are:

- *Pultruded fibre reinforced plastic obtained the best rating out of all the materials chosen.*
- *Due to lack of field experience of fibre reinforced materials in the area of VAWT blades a large safety factor would be required.*
- *One method that is becoming quite popular and proving to be very cost effective is pultrusion.*
- *The scores for all the materials except aluminum may be quite conservative due to the fact that the exact processes to manufacture the blades and the behaviour of the blade once in use are fairly unknown. Upon further*

analysis of these materials may prove to have a substantially better rating than aluminum.

Pultrusion is a continuous forming process that allows for a very high glass fiber content, which results in a very high strength, yet flexible rotor blade and the basic material strength is in the order of 100,000 psi (689.5 MPa) or approximately twice the strength of low carbon steel [8]. In recent times, pultruded FRP blades have been preferred by one of the leading small HAWT type wind turbine manufacturer like Bergey [8] and a few other small wind energy conversion system [2].

5. Method of Design Analyses

For the design with variable turbine speed there appear many fixed and variable design parameters as shown in Table 1. The values of the parameters used for the present analyses are shown within the parenthesis. Based on these parameters, the design analyses have been carried out in this research work and the results are presented in the next section. Details about the overall design method and the fixed and variable parameters, shown in Table 1, can be found in reference [1]. For the present analyses, material properties found in reference [2] have been used for determining the allowable stresses (S_a) of aluminum and FRP which are being investigated in the present study. The allowable stress for aluminum is selected as 90 N/mm^2 which is below its fatigue strength of 97 N/mm^2 in $5X10^8$ cycles. As per suggestion of CETC [2], a large safety factor of about 3 is used for FRP. The allowable stress for FRP is selected as 170 N/mm^2 which is below its fatigue strength of 175 N/mm^2 in $10X10^8$ cycles.

6. Design Analyses with SB-VAWT Blade Materials

In this section, comparative design analyses have been performed with two prospective materials – (a) Aluminum and (b) Pultruded FRP. As mentioned earlier, Aluminum has been extensively used by VAWT manufacturers in the past. Though pultruded FRP has been utilized by HAWT manufacturers, its application with SB-VAWT is not established yet. However, it can be considered as one of the prospective material for SB-VAWT based on the study conducted by CETC [2] as they are economically attractive and they have a good combination of material properties like: moderate stiffness, high strength, and moderate density.

Results obtained from the design analyses of a variable speed SB-VAWT at different design wind speeds are presented in Table 2 for Aluminum and FRP as blade materials. The design wind speed of the turbine is varied between 10 and 15 m/s. It can be seen from Table 2(a) that chord, diameter and height of three types of turbines decrease with the increase of wind speed. This happens as a consequence of decreasing swept area because of increasing wind speed for a fixed power coefficient. In Table 2(b), the variation of blade skin thickness (t_s) and the mass per unit height (m_b) are shown. For both the blade materials, t_s and m_b are decreasing with wind speed.

It can be seen from Table 2 that there is noticeable difference between the two materials in the values of c, D, t_s and m_b. The values of these parameters are lesser for FRP than that of Aluminum which is attractive from design point of view. Furthermore, the values of design aspect ratio (H/c) of a SB-VAWT with FRP blades are higher than that of Aluminum. It should also be stated that, judging from the selected allowable stresses of these two materials, it is expected that FRP will endure $10X10^8$ cycles which is double of aluminum's fatigue load cycles ($5X10^8$) during their lifetime. This is obviously a significant advantage for FRP over aluminum based on their fatigue strength. Based on all these findings, the superiority of FRP as blade material of SB-VAWT over conventionally used aluminum is clearly demonstrated.

7. <u>Conclusions</u>

In this paper, required properties of the SB-VAWT blade materials are first identified. Then available prospective materials are shortlisted and assessed. Subsequently, comparisons are made between the available materials based on their mechanical properties and costs. The pultruded FRP has been found as a prospective alternative blade material for SB-VAWTs. Then detailed design analyses have been conducted with two materials, namely (a) Aluminum and (b) FRP. The results of the design analysis demonstrate the superiority of pultruded FRP over conventionally used Aluminum.

8. Acknowledgements

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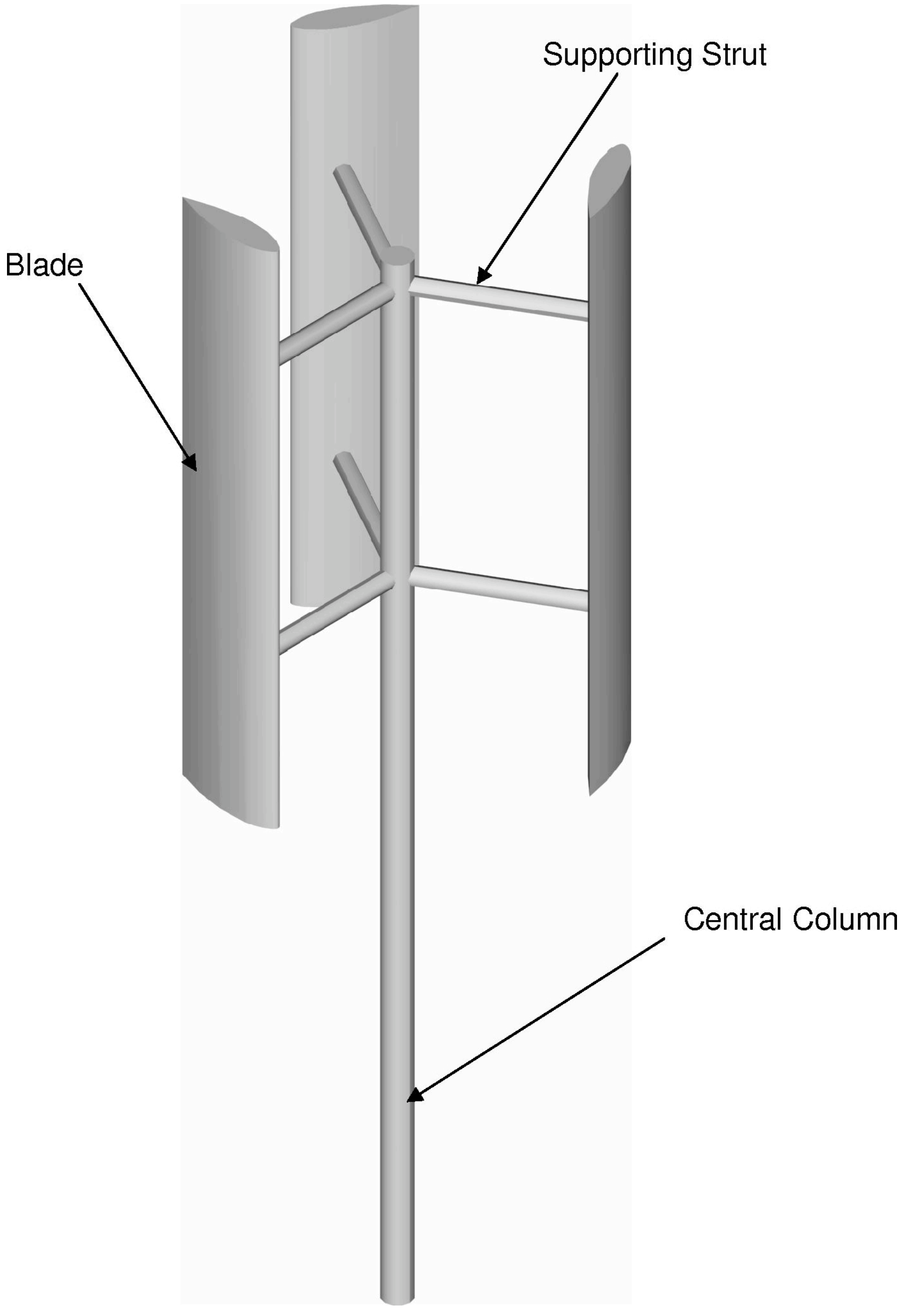

Figure 1: The Main Components of a Typical SB-VAWT

Table 1: Different Fixed and Variable Parameters for the Design Analysis

Design Parameter	Value
1. Blade Airfoil	Fixed (MI-VAWT1)
2. Number of Blade (N)	Fixed (3)
3. Supporting Struts type	Fixed (Overhang type)
Supporting Struts shape	Fixed (MI-STRUT1)
4. Swept Area (A=2RH)	Variable
5. Solidity (Nc/R)	Fixed (0.5)
6. Aspect Ratio (H/c)	Variable
7. Rated Power Output (P_o)	Fixed (3 kW)
8. Rated Wind Speed ($V_{\infty d}$)	Fixed (Altered from 10 to 15 m/s)
9. Cut-out Speed ($V_{cut\text{-}out}$)	Fixed (25 m/s)
10. Power Coefficient (C_{Pd})	Variable
11. Tip Speed Ratio (λ_d)	Variable
12. Rotational Speed (ω_d)	Variable
13. Pitching of Blade (γ_d)	Fixed (Fixed pitch angle of zero)
14. Load	Fixed (variable speed)
15. Material	Fixed (Aluminum or FRP)

Table 2: Design Configurations with Aluminum and FRP

(a) Overall Dimensions of the SB-VAWT at Different Design Wind Speeds

$V_{\infty d}$ (m/s)	Swept Area (m^2)		Chord (m)		Diameter (m)		Height (m)	
	Aluminum	FRP	Aluminum	FRP	Aluminum	FRP	Aluminum	FRP
10	12.1	12.0	0.35	0.27	4.3	3.3	2.8	3.7
11	9.1	9.0	0.31	0.24	3.7	2.8	2.5	3.2
12	7.0	7.0	0.27	0.21	3.2	2.5	2.2	2.8
13	5.5	5.5	0.24	0.19	2.9	2.2	1.9	2.5
14	4.4	4.4	0.21	0.17	2.6	2.0	1.7	2.2
15	3.6	3.6	0.19	0.15	2.3	1.8	1.5	2.0

(b) t_s and m_b at Different Design Wind Speeds

$V_{\infty d}$ (m/s)	Skin thickness, t_s (m)		Blade Mass per unit Height, m_b (kg/m)	
	Aluminum	FRP	Aluminum	FRP
10	0.011	0.008	24.8	9.8
11	0.009	0.007	18.5	7.4
12	0.008	0.006	14.2	5.7
13	0.007	0.006	11.3	4.5
14	0.006	0.005	9.0	3.7
15	0.006	0.005	7.4	3.0