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Construction and numerical analysis of a collapsible vertical axis wind turbine

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ABSTRACT

This study presents a design of an efficient mobile vertical axis wind turbine (VAWT) that is collapsible for relocation purposes. The wings of the turbine retract into the base shaft via a device described here within this article. The device does survive conditions up to 15 m/s winds and the unit can be raised/lowered in few minutes time. One of the main accomplishments of this research article was the manufacture of the blades from epoxy polymer reinforced with carbon nanotubes. About 7.8% enhancement on tensile strength was obtained by adding 0.75 (wt%) of CNT to epoxy resin. Mathematical simulations were conducted through MATLAB. Two working models were created of the turbine system. The first model was for tracking the forces on the hinges of the turbine assembly as the device rotates. Hydraulic forces acting on the shaft were calculated with the second MATLAB model. ANSYS was used to model the majority of the structural components. Data from the mathematical models were used to verify the structure of the turbine and shaft were within acceptable stress and strain limits. Field experiments were carried out and compared with the simulation results. The result of the experiments verified the mathematical simulation analysis.

1. Introduction

Wind energy is one of competitive renewable energy in Saudi Arabia and in several locations in the world. Wind turbines generate electricity by converting the wind energy into kinetic energy and the turbines turn to generate electricity [1]. Wind energy causes no pollution and produces no greenhouse gases during operation such as carbon dioxide and methane [2,3].

Over time, the concept of the VAWT has been developed into several mature designs that are used today [4–6]. The Savonius wind turbine operates similarly to an anemometer by using “S” shaped scoops to create enough drag to cause rotation [7]. This design is less efficient than the more recently developed Darrieus wind turbine [8]. Darrieus turbine has problems with a large torque ripple through each revolution, and the natural frequencies of the long blades required in the turbine must be avoided [9,10]. Also, this design is not self-starting [11,12] and the height of these turbines also requires the use of guy-wires or an external superstructure to keep the structure erect and stable. The Cycloturbine (H-rotor) uses straight blades or airfoils on an H-bar configuration to smooth out the torque ripple and allow the turbine to be self-starting [13]. The Gorlov turbine has a low torque ripple throughout each revolution, is self-starting, and has shorter blades to reduce the problem of vibration in the blades [14].

Currently, mobile wind power stations exist in a package that fits inside a standard shipping container. While the multiple-power system may be dropped in numerous locations, it is not easily portable without the use of cranes or helicopters. Another important point, as is well known, that wind turbine blade plays an important role in the overall performance of the turbine. More specifically, extraction of energy from wind depends on the design of blade. At present, for the most of small wind turbines, the blades are made with metal materials, while composite materials are generally used for large wind turbine.

To overcome the weaknesses points of former works mentioned earlier, the general design for the current study was made such that the wing bows out like the Darrieus while it is still a triple helix like the Gorlov. An important key difference in the design presented in this study and other current designs, the present wings were composed of a material which will retract into the base shaft via a device described in this article.

The first objective of this study is to design a mobile wind power station that may be quickly compacted and removed from the site so it will not be damaged in adverse conditions. This would be relatively small, but have the ability to power a simple command center for civilian or military efforts. Another objective is to conduct an experiment

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to verify the performance and reliability of the designed mobile wind power station. The last objective is to offer a new avenue for the designing and manufacturing of composite blade used in small-scale VAWT.

2. Design and preparation of blades

The blades in the operating process of VAWT bear the function of centrifugal force caused by rotating and aerodynamic loads, which put forward high requirements for blade strength and its resistance to deformation. Extraction of energy from wind depends on the design of blade. One of the methods to modify stiffness and stability of the blade is to change its shape, but this could affect aerodynamic efficiency of wind turbine. On the other hand, changing the dynamic and mechanical properties of wind turbine can be done by modifying the composite material, which the blade is made of. For this reason, the most challenging of tasks in this design was the design and preparation of the composite blades for the small VAWT. This resulted in light weight and high strength blades which can affect the performance of the vertical axis wind turbine and its extraction of the wind power. Research studies in the literature presented strong evidence that carbon nanotubes have remarkable mechanical properties. Due to their exceptional thermo-mechanical, chemical and optoelectronic properties, carbon nanotubes (CNTs) are becoming increasingly promising materials for modern technology applications (nanocomposites, nanodevices, nanoelectronics, nanomedicine). Low pressure chemical vapor deposition (LPCVD) method was used in this study to grow the carbon nanotubes. In this method, a substrate of silicon wafer was coated with iron nano particles as a catalyst using LPCVD machine manufactured by Syskey technology Ltd. Ferrocene was used as a catalyst while acetylene (C_2H_2) was used as a carbon precursor along with nitrogen (N_2) as a process gas. The average diameter and length of the carbon nanotubes produced were found to be 20 and 1000 nm, respectively.

The produced carbon nanotubes were used to prepare epoxy resin samples which contain 0.75 (wt%) of carbon nanotubes. The preparation procedure for each sample was as follows. First, specific weight of carbon nanotubes (0.75 wt%) was dispersed in ethanol and mixed mechanically for 10 min at 2000 rpm. Then, epoxy resin was added to this solution. Ethanol was used as solvent to dilute the epoxy resin. Next, in order to obtain homogeneous dispersion, the mixture was sonicated by an ultrasonicator machine, BRANSON 2510, for 12 h. For the removal of the ethanol, the mixture was then placed in a low-power ultrasonic bath (BRANSON 2510) for another 12 h. The residual ethanol was removed by evaporation in vacuum. After that, a hardener was added to the combination and mechanically mixed for 20 min. The hardener (curing agent) was cobalt naphthenate, approximately 53% in mineral spirits (6% Co) and MEKP (Alfa Aesar®, Johnson Matthey Management GmbH & Co Karlsruhe Germany). The only exception to that was the 0 wt% CNT sample where the epoxy resin was mixed with the hardener directly. The 0 wt% CNT sample was prepared to evaluate the effects of adding CNTs on the tensile strength of the composite samples. When the mixture was ready, the following work was done orderly: lay-up the mixture in a pre-prepared airfoil blade mold which was prepared according to the required design thickness and shape of the blade, brush the mixture, close the mold, curing at room temperature, demold after solidification, remove the flash, and burnish. The final product was a blade with the required designed shape and dimensions.

To evaluate the effects of adding CNTs on the tensile strength of the composite samples, tensile tests were conducted on parts the cured samples according to ASTM D638 using the universal testing machine, INSTRON® 3369, at a load of 50 kN and a rate of 5 mm/min. Based on the results achieved, about 7.8% enhancement on tensile strength was obtained by adding 0.75 (wt%) of CNT to epoxy resin.

Table 1
The major parametric dimensions of the collapsible wind turbine.

VAWT structure	Twisted blade-rotor
Rotor radius	0.6 m
Number of blade	3
Blade height	5 m inclined vertically at 30°
Blade length	70 cm
Blade width	15 cm

3. Concept design and development

Table 1 summarizes the major parametric dimensions of the twisted blade-rotor. The intended structure was developed so that it can be configured into two structural modes: operational and storage. Operational state is defined as the turbine being capable of generating electricity from the wind in its environment. Storage mode is defined as the turbine being in a collapsed state such that the device can be safely transported via conventional trucking methods outside of its normal operational mode. In its final design, the device uses collapsing arms and track to position itself on the semi-trailer. When in operational mode, the apparatus is structurally sound for wind velocities normally encountered on earth. To do this, the stresses and deformations of all components of the structure do not exceed the set safety factor of 3 when presented to winds in velocities up to 15 m/s (which is at hurricane category 1 classification). There was no code or a guideline for setting the safety factor of 3 in all components but to validate the design (able to withstand 15 m/s but not meant to feel more than 5 m/s). The transportation trailer was also designed to provide a structurally sound base using extendable legs to provide more stability in these high wind conditions. To analyze the natural effects on the turbine in operation, a spreadsheet has been developed that breakdowns the various values for load on the wings, RPM of the turbine, and other information. Simulations of this information can be found in later section.

The wind turbine was designed to collapse down to manageable conditions for transport. The transition between fully stored and fully operational takes no more than few minutes and occurs at the push of a button, given normal operating conditions. This is carried out using a hydraulic cylinder to raise the device. For raising the device, a hydraulic cylinder was used to complete the job without risking creating an ostentatious piece of equipment. At its point of peak operation, the cylinder supports ~2.67 MN. A hydraulic cylinder from Custom Hoists Inc. set to support the load at 27.2 MPa, with a piston area of 482 cm^2, was selected for the job. Since the actuator would be required to travel a total of 1 m in the stroke, an estimate for the amount of fluid required for the device was calculated at 1.1 m of length. This produced a grand total of 0.31 m^3 of fluid for the cylinder, which adds approximately 319–3281 N to the trailer (based on a density of 873 kg/m^3 given for Esso Imperial Hydraulic Oils).

The application of the Gorlov design allows the turbine to self-start in slow wind speeds. The design facilitates the blades to begin moving with wind speeds as low as 0.8–1.4 m/s while having the ability to produce electricity at 2.2 m/s.

The collapsible, mobile, vertical axis wind turbine is 5 m in height and when collapsed lays flat on an 8 m trailer modified for off-road and heavy usage applications. Fig. 1 depicts the structure in both operable and collapsed forms. The blades have hinges perpendicular to the center of the shaft. Arms, attached by pins to the blades, are pinned to a circular bearing that travel tangentially around another bearing that can move up and down the shaft. This lets the drive shaft rotate freely as well as allowing the blades to be brought in close to the shaft while not in use. The next step was to design the arms and hinges that would connect the arms to the center shaft and allow them to fold down. A shallow oval shape was chosen for the arm instead of an airfoil to ensure that there would be no lift on the arm that would counteract or interfere with the lift on the blade. The hinge is a simple butt hinge with