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Computational performance analysis of an airborne rotor-type electricity generator wind turbine

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Abstract. This paper presents an analysis of the possible performance of a proposed airborne rotor type electricity generator wind turbine design. The innovative design proposal by inventor is based on the rotation of the airborne structure with blades attached to the airborne zeppelin and thus it is called an airborne rotor generator. In this paper computational fluid dynamics analysis of a model close to the proposed design is carried out and the results are presented. The proposed design examples are set to produce 10-100KW. The electrical energy generated through two symmetrically placed alternators at both ends of the zeppelin is transferred to the ground-based system through the tethered cords used to also stabilize the system. Thus, an airborne rotor generator is formed.

1 Introduction

Airborne energy generators are being designed developed and tested by several laboratories around the World. Ahmed, Hably and Bacha Ahmed, Hably and Bacha [1] and Fagiano and Milanese [2] have prepared papers on companies in development of airborne wind turbines (AWT). In their review of airborne wind energy systems technologies, Antonello Cherubini et.al [3] have attributed two main types of airborne wind energy systems (AWES) as Ground-Gen and Fly-Gen design groups. In the ground-gen group, electricity generator alternator systems are on the ground and in the Fly-Gen group the total generator group is in the air and the electricity generated is transferred to the ground by tethered wires. An analysis of Fly-Gen Group gyroscope-type airborne wind turbines is presented by D. Rancord et.al [4] in which a four rotary wings provide the lift to a flying vehicle and excess power extracted is transferred to the ground through electrical conductors embedded in a structural tether. Fly-Gen systems under development are summarized in Table 1 by Antonello Cherubini et.al [3].

In their study D. Rancord et.al [4] developed a lumped mass model of the Sky Wind Power (www.skywindpower.com) four turbine tethered quadcopter system to predict and analyze the performance of the system. In their work a design space exploration of the concept is performed. The physical breakdown of the system into wind profile, rotor aerodynamics, structural mass, electrical system, and tether is presented. Optimization efforts of the electrical power that reaches the ground indicated that the electrical conductors are the driving components of the system's overall efficiency. It was found that a generator operating at approximately 8000 m, an altitude lower than the jet stream, would produce the most electric power despite seeing lower wind velocities assuming conventional technologies.

Table 1. Breakdown of the companies developing Fly-Gen type airborne wind turbines (2015) Antonello Cherubini et.al [3].

General System Description	Company	Flying Principle	Type	Energy Gen. System
Turbines on a tethered aircraft	Makani Power	Wings Lift	Crosswind	6/8 Turbines
	Joby Energy	Wings Lift	Crosswind	Several Turbines
Tethered quadcopter	Sky Windpower	Rotors Thrust	Non-crosswind	4 turbines
Turbine on a lighter than the air balloon	Alteros Energies	Buoyancy	Non-crosswind	1 turbine

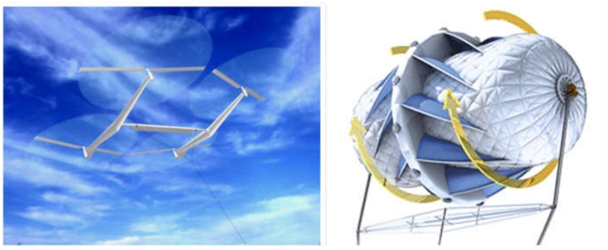

Fig 1. a) Sky Wind Power (www.skywindpower.com) 4 turbine tethered quad-copter system
b) Sketch of MAGEEN-Type Air Rotor System (MARS) by Bryan Christie

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In this paper, a computational fluid mechanics (CFD) tool is used to model and analyze the possible performance of the MAGENN Type Airborne Rotor System (MARS) [4] (Figure 1b) which is a revolutionary idea of a rotating zeppelin as the rotor of the wind turbine. This concept is invented by Inventor Fred Ferguson.

2 Magenn-type Airborne Rotor System (MARS) components & computational model developed

Although airborne wind turbines (AWT) are multidisciplinary systems, in the present study aerodynamic performance of a MAGENN type airborne rotor system will be analysed.

Seifert,J's [5] review on the Magnus effect in aeronautics is an in depth work on the exploration and application of the lift force due to a cylinder in cross flow. Due to the Magnus effect, which is the resultant lift force produced on a rotating cylindrical object in uniform cross flow, this type of lighter than air (Helium used) generators are also lifted by this force in addition to buoyancy force.
One of the many interesting examples is the ship Baden-Baden in the picture in Figure 2.

Fig 2. Rotor Ship Baden-Baden & Enercon -EN-1 Craft T. et.al. [6] © Springer Science+Business Media Dordrecht 2013

Craft T. et.al. [6] have revisited the use of this phenomenon in their article and reviewed the application of the phenomenon in 21st Century.

Chaudhari [7] presented a summary of the possible working systems of a MARS Prototype (estimated production capacity of 10-100 KW for wind speeds ranging 3-28 m/s at 120 to 300 meters) tested and improved at Vigyan Low Speed Wind Tunnel https://www.vigyan.com/magenn---mars.html).

The Model was tested in Vigyan tunnel tests to assess the turbine's lift, drag and torque for the determination of the power output.

In the present study several wind speeds will be used to estimate the lift and torque produced by a rotating MARS model as shown in Figure 3. A computational fluid dynamics (CFD) model is formed and possible wind energy conversion and performance indicators are reported.

Fig 3. MAGENN (MARS) prototype (https://newatlas.com/magenn-mars-floating-wind-generator/11109/#gallery inventor: Fred Ferguson (https://patents.justia.com/assignee/magenn-power-inc)

The possible wind energy and power density distributions are studied and reported by Archer and Caldeira [8]. Wind power density (δ) is a function of density and velocity. The average velocity at a certain height and location may be assessed by using the below formula and predicted wind power density.

$$\delta = (1/2)\, \rho\, V^3 \quad (1)$$

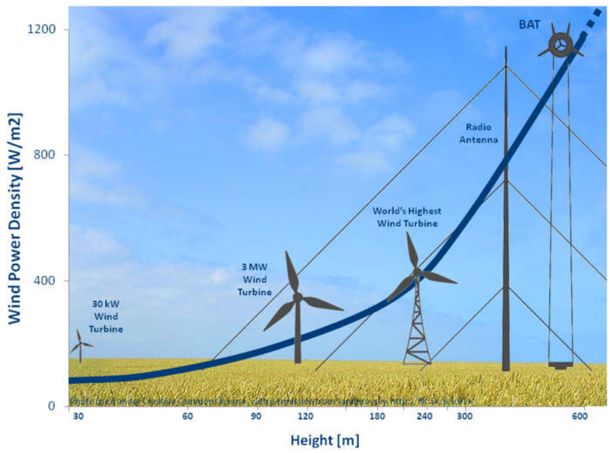

Fig 4. Illustration of average wind power density with height. Adopted from (http://www.euanmearns.com/wp-content/uploads/2016/06/infographic_highaltitudewind.png).

In the analysis of the performance prediction of a 240kW flying electric generator developed by Sky Wind Power (www.skywindpower.com) Roberts et.al [9] estimated the average velocity to be used between heights of 500-5000 meters using data from, Caldeira [10], O'Doherty and Roberts [11] , Atkinson et al. [12].

$$V = 14 + 5.7\,(H / 1000) \quad (2)$$

where H is the height.

2.1 Physical modeling for the aerodynamic analysis of the rotating zeppelin with blades

The physical model to be used in computational fluid dynamics calculation of a MARS model to be analyzed using the ANSYS/FLUENT program [13] requires development and construction of the solid model of the Generator to be transferred to the CFD calculation environment. Inlet and outlet wind conditions together with interior properties (i.e. density, velocity, pressure, turbulence intensity, turbulence model to be used, rotational speed of the model) are to be determined.

2.2 Solid model of the MARS airborne rotor prototype

Details of the model developed by inventor Fred Ferguson are not known. In this study a parametric study of possible performance values, hence near exact values for geometries, are used. Figure 5 shows the Solid Model developed.

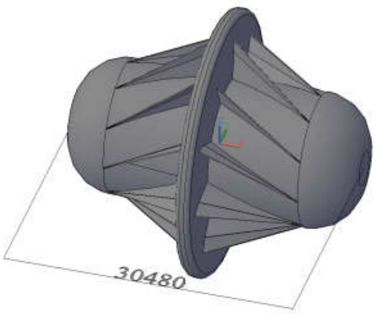

Fig 5. Geometry of the MARS airborne rotor

3 Computational solution domain properties

Solid Model developed is imported to ANSYS/FLUENT Program [13] and a solution domain is constructed with around 1,400,000 elements.

2.1 Mesh structure

Figure 6 shows the mesh structure on the rotor faces.

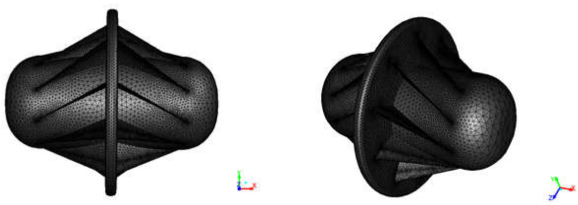

Fig 6. Mesh structure of the rotor

Solution domain mesh structure is shown in Figure 7.

Fig 7. Domain mesh structure.

The domain mesh has 351,963 nodes and 1,936,144 elements.

4 Results

Inlet boundary condition is wind velocity and outlet condition is gauge pressure.

The surroundings of the solution domain is assumed to be symmetric. RANS calculations for k-epsilon turbulence model are carried out.

Converged (1.0E-03 residual for continuity) solutions for wind velocities of 4,6,8,10,12,14 m/s are obtained and analyzed. Figure 8 illustrates pressure contours from the wind direction on the rotor.

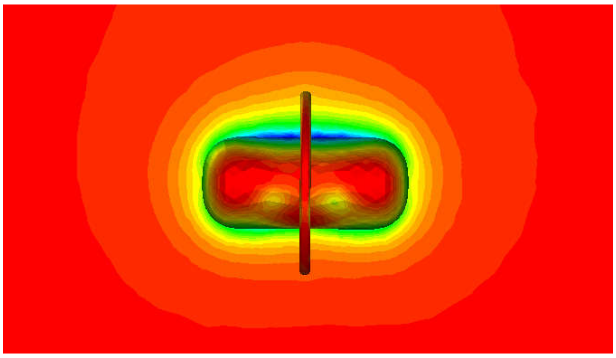

Fig 8. Pressure Contours on Front (Wind Direction) side of the Rotor with no blades.

It is assumed that the tip velocity of the rotating blades is around 0.9 of wind speed. Rpm is calculated and rotation is applied to the rotor at the calculated angular speed. Results for 12 m/s wind speed (published rated speed) and 12.76 rpm are presented for a time lapse of 15 seconds (13.5 degrees of rotation) in the following figures.

RANS solutions indicated that a k-omega turbulence model may capture the local vortices better. Hence, the solution for wind velocity of 12 m/s is used as an initial solution and k-omega model is applied. Following these results, it is decided to investigate an unsteady solution (URANS). The presented results are (Figures 9-12) from the URANS solutions which are continuing to explore.

Possible power generated is calculated from Moment (Torque) predictions in each case. Results indicate that a power production of 5 to 90 kW is expectable at wind speeds from 4-12 m/s with wind power density 29 to 1106 (W/m2) (which is expectable at heights around 300 m (Figure 4).

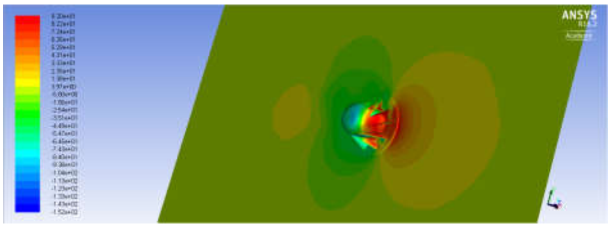

Fig 9. Pressure (Pascal) contours for 15 seconds (initial zero degrees)

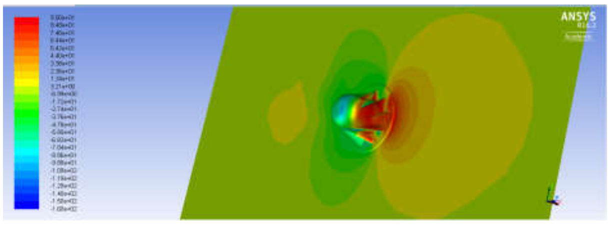

Fig 10. Pressure (Pascal) contours for 30 seconds (13.5 degrees advanced)

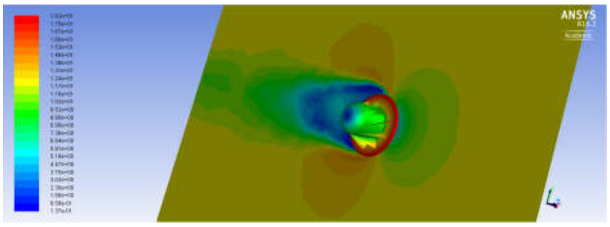

Fig 11. Velocity (m/s) contours for 15 seconds (initial zero degrees)

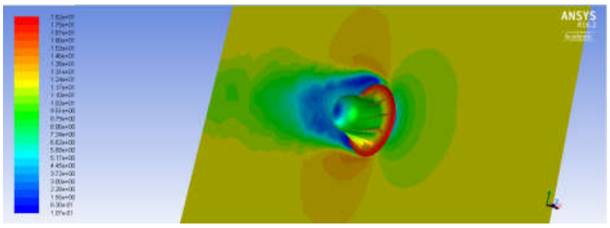

Fig 12. Velocity (m/s) contours for 30 seconds (13.5 degrees advanced)

5 Conclusions

In this paper computational fluid dynamics (CFD) work is carried out to analyze the possible power production of an airborne rotor type wind energy generator invented and developed by inventor Fred Ferguson (https://patents.justia.com/assigneen/magenn-power-inc).

The dimensions are close to the specifications found in open literature. The model(s) developed were tested and improved at Vigyan Low Speed Wind Tunnel https://www.vigyan.com/magenn---mars.html). It is proposed that a peak power of 100kW is possible wind speeds 11-12 m/s altitudes of around 150-300 meters.

Results estimated in this study indicate that the occurrence of such power ratings with wind power density of around 1100 kW at these altitudes is possible with a power coefficient, Cp, of around 11.6%. Additional lift force due to Magnus effect (https://www.norsepower.com/technology and, Seifert J. [5]) is calculated to be between 300 N and 3000 N. The weight of the aero rotor with tether is reported to be 3000 lbs or 1360 kgs. (around 13,500 N). Induced drag force varies between 4.5kN to 12.5 kN, which is sustainable by using special tether materials withstanding such forces.

Altaeros BAT design developed by MIT (2010-) uses a horizontal axis wind turbine within an Helium balloon duct (https://renewableworld.net/altaeros-bat-floating-wind-turbine/) and proposes around twice ground based wind turbine performance at altitudes around 600 m. At this height the expected wind power density raises to 1200 (W/m^2).

The Power Coefficient, Cp, value of 11.5% is lower than a well-designed vertical axis turbine on the ground (around 20 %) and much less than the Betz Limit [14] defined for horizontal axis wind turbines (HAWT) of 59.1%. Betz theoretical limit for a vertical axis wind turbine is not defined. However, a maximum of 0.22 may be assumed by referring to experimental results in literature.

The high performance reported by comparison for BAT may be due to; horizontal axis turbines used and calculations based on duct area and not the overall cross-sectional area of the structure with the balloon.

In this work the stability analysis of the structure due to different wind angles was not studied. The circular structure in the middle is assumed to act as a tail wing. The tether structure is assumed to have a special ending at the junction to enable rotation in both directions.

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