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Optimal Design and Comparative Analysis of Airborne Wind Turbine

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ABSTRACT: Increasing energy demands over the recent years has seen a rise in development of alternate energy sources. Wind being one of the most abundant and easily available source, is an excellent alternative to conventional energy sources. As the non-renewable sources of energies are drastically depleting, different power generation modes must be sorted out in order to meet the current and the future demands. Currently, there are solar panels, wind turbines, and hydrogen cells which are seen as an alternate to the conventional power sources, but their high operating cost per unit of energy produced makes them a limited option. The research presented in this paper aims to offer a unique alternate source of power generation. In order to meet the future energy demands, an optimal vertical axis airborne wind turbine is designed and performance analysis is carried on the same. In the proposed design, a lightweight vertical axis wind turbine is placed inside a diffuser shaped aerostat which is suspended hundreds of feet above the mean sea level mainly due to the presence of strong wind currents at high altitude.

KEYWORDS: Airborne wind turbine, Aerostat, Alternate energy source.

I. INTRODUCTION

Looking at the present energy trends, and irrational consumption of the planet resources it is not hard to say that the planet earth is progressing towards a great danger. The excessive dependency on the limited non-renewable source for the desired unrealistic exponential growth has endangered the fragile structure of the earth model. Throughout the world, consequences of the human action are felt as polar ice caps are melting leading to increase in water level and rise in atmospheric temperature worldwide. To counter this frightening situation scientific community has been constantly urging for transition towards more sustainable energy resources to satisfy escalating energy demands. Clean renewable energy sources are seen as an alternate to the non-renewable fossil fuel reserve. Scientists and researchers throughout the world are investigating renewable, cheaper, and more reliable sources of energy. The two most common renewable sources of energy, wind and the solar energy, are the epicentre of the current research on clean energy innovation. With the wind and the solar power being practically the inexhaustible energy sources, the potential to convert these energy sources to electricity is seen as the solution to majority of energy issues.

In past few years, exponential growth has been observed in the utilization of green energy technologies, especially for small-scale applications. This clearly depicts the window for technological advancements in this domain. Thus, the field of renewable energy sources are attractive not only environmentally, but also economically and politically.

In this research an optimized lightweight combined airborne wind turbine has been designed, whose idea has been drawn from ground based Savonius vertical axis wind turbine and an Aerostat. Main objective is to compare the designs in order to determine whether the proposed combined type of design produces more efficient results than Savonius design or not. Firstly, design and fabrication are carried out to come up with an optimized combined design. Then, a performance benchmark for classic Savonius wind turbine will be established. Later, results will be compared and conclusions will be drawn accordingly. A rigorous scientific methodology has been followed during the research in which claims are rejected or accepted depending on the results from the analysis performed.

The work in this paper is divided in two stages. 1) Design and Fabrication 2) Simulation and Analysis. For the first stage, CATIA[®] software is used to design optimal wind turbine and light weight aerostat individually, which are

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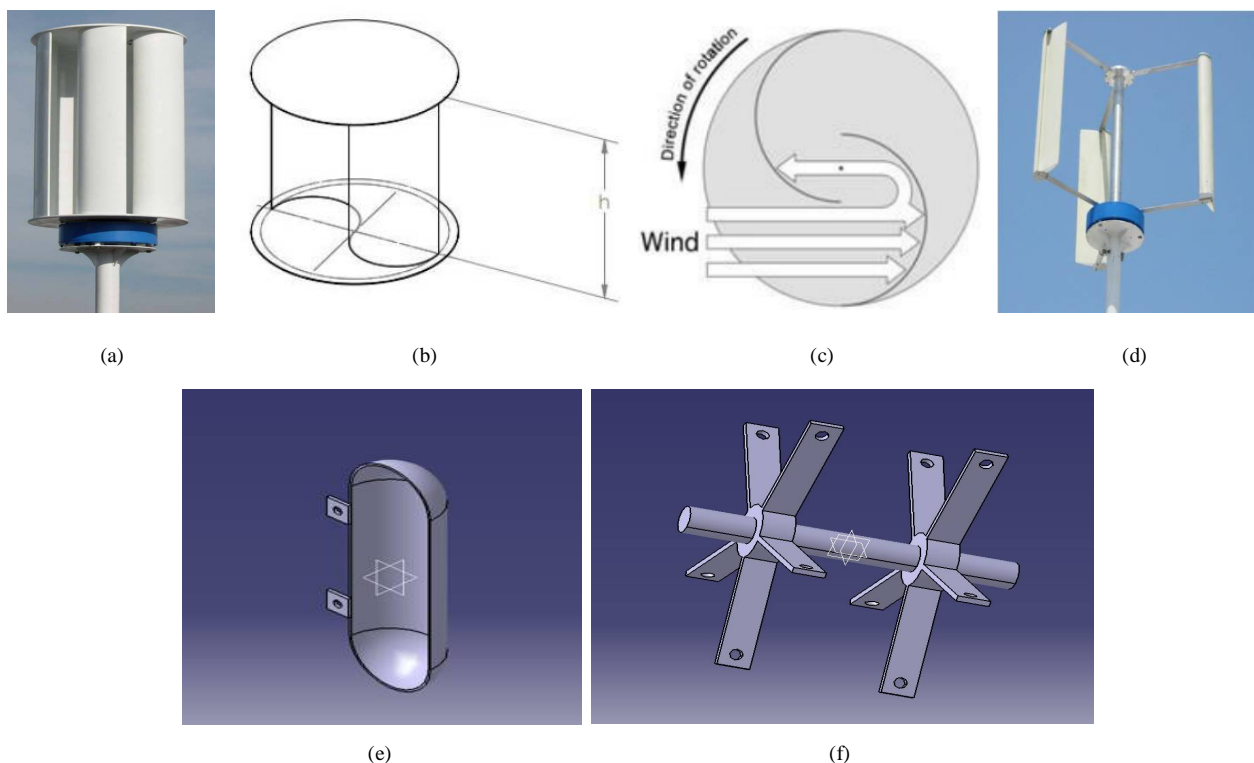
clubbed together using the same software. For the second stage, ANSYS FLUENT[®] software has been used to simulate and analyse the combined design whose results are compared with the classic Savonius wind turbine. Paper is organized as follows. Section II describes classic Savonius wind turbine based optimal modified wind turbine, light weight aerostat design, and assembled optimal light weight airborne wind turbine. Computational fluid dynamics analysis is carried out on the modified classic Savonius design, which is presented along with the experimental results, and comparative analysis in Section III. Finally, Section IV presents conclusion.

II. DESIGN AND FABRICATION

For the design and fabrication part, CATIA[®] v5 software is used which allows the creation of 3D complex designs. Objective of this research is to test the optimised design and compare the results with that of standard design. In order to come to optimised solution, first pre-existing classic barrel Savonius design has been taken in consideration which is modified using unique blade design arranged in Darrieus type blade configuration with a shaft and mounting plate arrangement. Newly modified design was housed in a cylindrical helium aerostat. Results were obtained from the tests on the classic barrel Savonius rotor design which were later compared with that of the modified design in the simulation phase, presented in the next section.

Design of optimal modified wind turbine

Barrel rotor design is quite simple. The basic concept behind the classic Savonius rotor comprising of two blades is that the blades are half a barrel which are set far apart and does not meet the axis. However, for this research classic Savonius design comprising 5 blades is taken as standard reference.

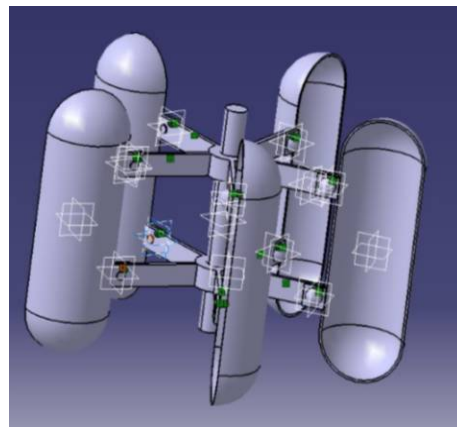


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(g)

Figure 1. Design and Fabrication (a) Classic Savonius wind turbine (b) Two blades Savonius rotor design (c) Overlapping of the classic Savonius half cylindrical rotor blades (d) CATIA® design of modified turbine blade (e) CATIA® design shaft with locking plate assembly(f) CATIA® design of modified vertical axis wind turbine

For the modified design, turbine blades of classic Savonius wind turbine encased with semi-cup shaped rounded part on both sides in order to trap more air. These modified blades are then arranged in Darrieus type of blade configuration with a shaft and mounting plates arrangement. For structural integrity, shaft along with mounting plates is mandatory as it supports the turbine blades against drag force produced by the wind while pushing the rotor blades.

Design of Aerostat

To house the modified wind turbine, an optimised aerostat is designed which exploited both Helium gas and wind energy to stay at a higher altitude. Tremendous saving in terms of weight, complexity, and cost is offered by the “Variable-Volume Bridle” property which allows aerostat to stay at 6000 feet without any necessity of ballonet. Also, kite spar made up of carbon-fiber is utilised which provided useful shapes at the time of low pressure.

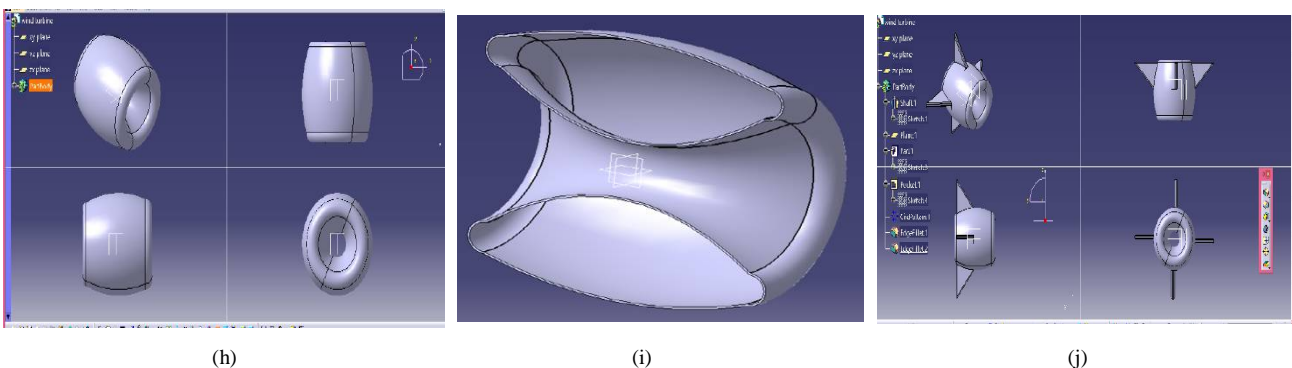


Figure 1. Design and Fabrication (h) Balloon model (i) Cross-sectional area of balloon model (j) Balloon model with Stabilizer

The aerostat design of 11 m³ of Helium gas allows it to lift 5.5 Kg in zero wind at 3000 feet altitude and 2 Kg in slow winds at 7000 feet altitude. Mounting at high altitude ensures continuous availability of wind.

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Assembled Design

Modified wind turbine is housed within helium filled balloon or aerostat which is stabilized with the means of directional stability which is alienated from weathercocking.

III.SIMULATION AND ANALYSIS

For simulation, the geometry designed in previous stage is imported to ANSYS FLUENT® software which allows CFD analysis. Imported geometry is meshed and then boundary layer is defined through GAMBIT software.

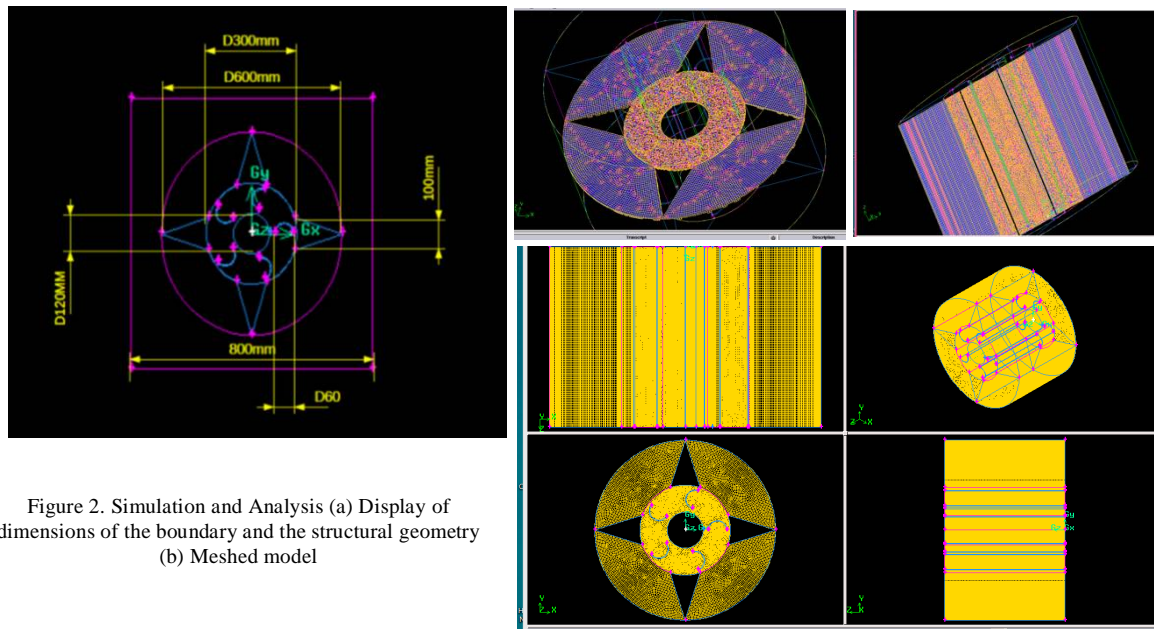


Figure 2. Simulation and Analysis (a) Display of dimensions of the boundary and the structural geometry (b) Meshed model

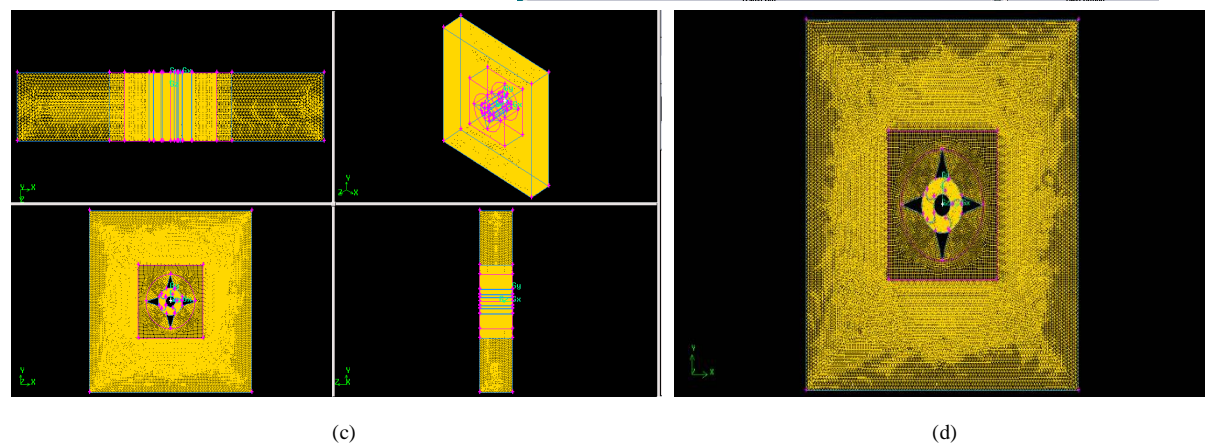


Figure 2. Simulation and Analysis (c) Meshed Volume (d) Front view of meshed volume

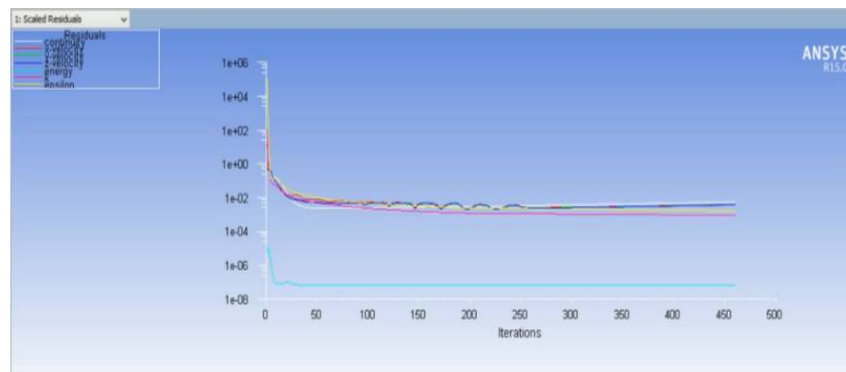
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Once boundary is defined, mesh file is loaded and simulated in ANSYS FLUENT® software. System is iterated for certain set of values which is concluded once convergence curve is obtained.



(e)

Figure 2. Simulation and Analysis (e) Convergence curve

For the analysis, simulation was run for 2, 3, and 4 m/sec on the positive axis (from left to right). Same solver and settings used for all the 2D simulation test cases.

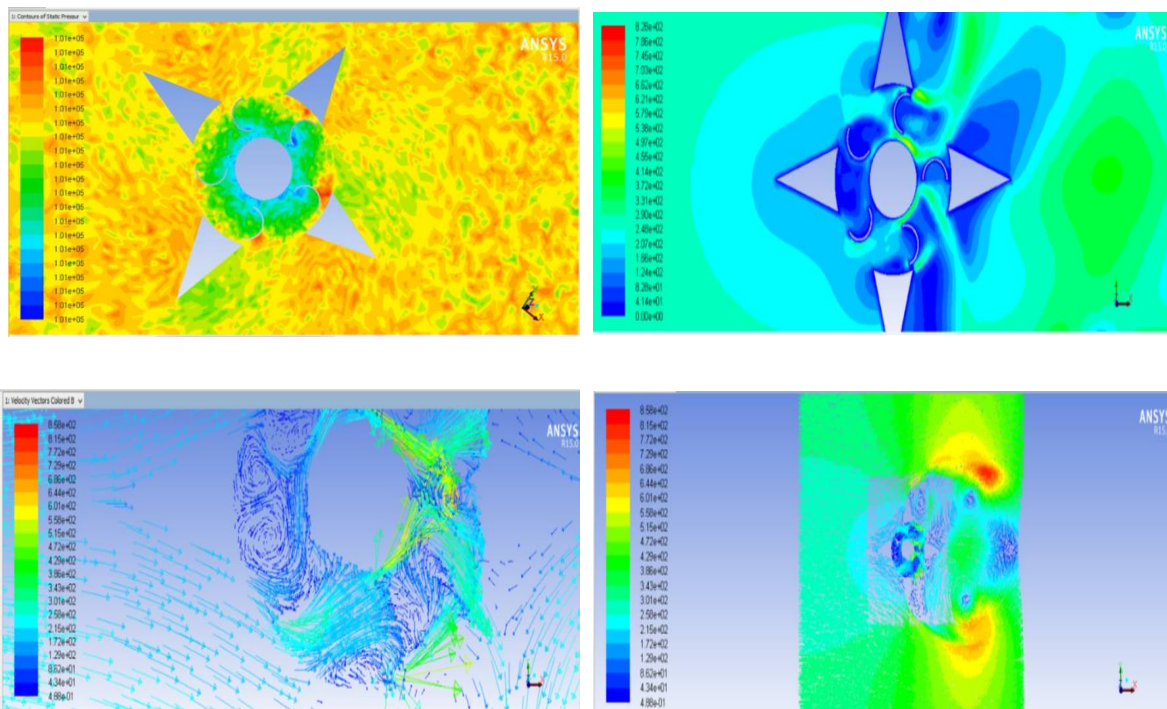


Figure 2. Simulation and Analysis (f) Static pressure contour (g) Velocity magnitude contour (h) Velocity vector (i) Velocity vector with velocity magnitude

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Moment being the product of distance and force means that low moment is generated by the pressure values closer to the axis in comparison to same pressure values far from the axis. This is the feature of modified turbine design. Using the same surface area as Savonius wind turbine i.e., same amount of material, modified turbine design is able to produce high values of pressure far from the axis. So, the hypothesis is whether modified design will be able to produce higher moment compared to the standard Savonius design.

Computational analysis stated high pressure on the concave side of the rotor blade (the receiving open cup) as this is where wind will strike the most and will not escape fast enough as on the convex side. Behind the turbine rotor, negative pressure is observed (or vacuum gauge pressure with respect to atmospheric pressure) which gives a logical explanation as this is case where rotor is in static mode fixed in a specific orientation. Net force on the blade is caused due to pressure differential, thus, resulting in rotation.

From the design it is concluded that the design generates a high overall moment. The net moment experienced, at wind speed of 2 m/sec, by the modified optimal wind turbine rotor at an 30° orientation is 0.18 Nm which is more than 4 times as compared to the net moment generated by the classic Savonius rotor which is 0.04 Nm at the same orientation. This proves the hypothesis to be correct.

Comparative results of the modified optimal wind turbine design with that of the classic Savonius wind turbine design for different wind velocity profile is presented in table 1, table 2, and table 3.

Table 1: Angular velocity

Wind Speed (m/s)	Modified wind turbine (rad/sec)	Classic Savonius wind turbine (rad/sec)
2	33.78	16.84
3	57.25	43.40
4	61.54	50.85

Table 2: Angular acceleration

Wind Speed (m/s)	Modified wind turbine (rad/s ²)	Classic Savonius wind turbine (rad/s ²)
2	0.72	0.25
3	2.07	1.66
4	2.73	2.26

Table 3: Torque

Wind Speed (m/s)	Modified wind turbine (Nm)	Classic Savonius wind turbine (Nm)
2	0.18	0.04
3	0.30	0.25
4	0.46	0.34

IV. CONCLUSION

The main objective of this research is to design and analyse the performance of modified optimal airborne aerostat mounted wind turbine and compare the results with the classic Savonius wind turbine. From 2D simulation analysis it is concluded that modified design comprising of 5 blades is the optimal design as highest-pressure difference is generated on the ambient wind receiving blade at higher altitude. Thus, proving modified design to be a winner as combined type experienced higher torque (more than 4 times) mainly due to generation of high pressure far from the axis, in comparison to conventional Savonius wind turbine design.

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