Undergraduate School of Mechanical Engineering

Aerodynamic Analysis and Rapid Prototyping of a Spiral Wind Turbine

Bernabe I. Matus
4010H264

Advisor:
Dr. Wang Song Hao

Department of Mechanical Engineering
Kun Shan University of Science and Technology
#195 Kun Da Rd., Yong Kang District, Tainan City, Taiwan (R.O.C.)
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Instructor's Name: Sønghao Wang

Student's Name: Berrake Tsoi Matus

Student Identity No.: 40101264

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I. ABSTRACT

Wind power is one of the most important and cleanest sources of renewable energy available to date. Wind-turbines work by extracting kinetic energy from the wind to generate energy. Currently research is being carried out to improve the performance and design of wind turbines. In this study Computational Fluid Dynamics (CFD) software package FLUENT found in ANSYS Workbench was used because it offered an inexpensive solution to the analysis of the turbine. A horizontal axis wind turbine is presented, introducing the use of a spiral design for small turbine applications. The study will observe the aerodynamic performance of the blade for different wind velocities and revolutions per minute. Rapid prototyping was used because it allows for the visualization of the geometry and allows for improvements in design if necessary. The rapid prototyping method used was three dimensional (3D) printing and the monoFab ARM-10 3D printer was used to create a scale size of the turbine.
II. INTRODUCTION

The world dependency on fossil fuels and other non-renewable energy sources has brought about great anguish and damages to the earth and its inhabitants. [1] The use of fossil fuels have led to the increase of the annual greenhouse gas (GHG) arising from the global energy sector. The use of fossil fuels continues to dominate the global energy market despite the greater development of low-and zero-carbon technologies. Without the support of policy and actions by governments, GHG emissions, mainly from fossil fuels combustion are projected to rise. Mitigation has therefore become even more challenging. The continued and rapid release of the stored carbon in fossil fuels into the atmosphere is no longer environmentally sustainable. This has led countries to explore alternative energy sources. These sources include nuclear, hydro, wind, etc. the former two causing large environmental problems.

![Figure 2.1 Total Primary Energy Supply by resource 1993, 2011 and 2020](image)

Figure 2.1 Total Primary Energy Supply by resource 1993, 2011 and 2020 [2]
From the available renewable energies, wind generated energy is the one that cause the least environmental impact. The impact of wind energy is summarized on the table below.

<table>
<thead>
<tr>
<th>Habitat impacts</th>
<th>Coal</th>
<th>Natural gas</th>
<th>Oil</th>
<th>Nuclear</th>
<th>Hydropower</th>
<th>Wind</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air and water pollution</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Global warming</td>
<td>✓</td>
<td></td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Thermal pollution of water</td>
<td>✓</td>
<td></td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Flooding of land</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Waste disposal</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Mining and drilling</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Construction of plants</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>✓</td>
</tr>
</tbody>
</table>

Because of the relative safety of wind-generated energy, it has gathered great support and many countries have invested in researching the technology. The figure below shows the continued increase of wind energy.

Figure 2.2 Regional consumption pattern 2014 [3] (Percentage)

Table 2.1 Comparison of habitat impacts of wind energy to other energy sources [4]

Figure 2.3 Global cumulative installed wind capacity 2000-2015 [5]
A wind turbine comprises of several parts such as the generator, rotor, yawing system etc. This parts are made much efficient and are of higher quality because of the research carried out on these parts. A wind turbine’s basic principle is as follows: the wind turbine is driven by the wind and rotates at a predefined speed in terms of the wind speed, so that the generator can produce electric energy. Throughout the past and present years there has been much research being done on geometry of the blades to increase the efficiency of wind turbines. The research has lead in designs that are more efficient when compared to early version of a wind turbine. In the past, research and study on wind turbines were limited to the sources available. The development of a computer code has provided a feasible manner to study wind turbines. The aerodynamic of a wind turbine can be studied using computational fluid dynamics. This method employs numerical methods and algorithms to solve and study a problem. This manner of studying wind turbines use less time and resources.

With the increase of solid waste pollution, there has also been an increasing change in the manufacturing industry. The manufacturing industries are now striving to reduce their carbon footprint. Many people have started to adapt a greener lifestyle and recycling of solid waste is on the rise. Three dimensional (3D) printing is a Rapid prototyping method that demonstrates a friendly approach to manufacturing and design. 3D Printing is used to assist the visualization of a computer aided design model or for production. This process allows for the early detection of issues with the model and therefore reduces the cost and waste of material on the production line. 3D printing also saves material as it prints layer upon layer to create the model, meaning that it only uses the material needed and no more. This process is also perfect for replacing parts that are not crucial for operation. Instead of tossing the entire item, the part can be custom printed and applied and thus extending the life time of the product. This is good for the environment as it saves
large amounts of the energy that is involved in the manufacturing of the product. The different application of 3D printing can be observed on the chart below.

![3D Printing Applications Chart](image)

**Figure 2.4 Three Dimensional (3D) Printing Applications [30]**

### III. WIND TURBINES

#### 3.1 Small Scale Wind Turbines

Small scale wind turbines can be classified as vertical axis wind turbines (VAWT) and horizontal axis wind turbines (HAWT). VAWT are designed so as for the generator and transmission devices to be located at ground level. Furthermore it has the capability of capturing the wind from any direction without the need to yaw. HAWT have their rotor positioned at the top of a tower where the winds have more energy and are less turbulent. The shaft in a HAWT is mounted horizontally to the ground. This type of turbines have a yaw system that turns the rotor.
**Figure 3.1.1 Vertical-axis wind turbine and (b) horizontal-axis wind turbine [1]**

Wind turbines can also be classified in two types: A resistance type turbine and a lift type turbine. A resistance type rotor is generally made out of flat surfaces with a tip speed ratio smaller than or equal to 1. The tip speed ratio is the ratio between the rotor blade’s tip speed at its and the wind speed. TSR = (speed at blade tip) / (wind speed) [12]. The lift type turbine works like an aircraft’s wind, generating a lifting force in relation to the blade. The tip speed ratio in this type is larger than one. This make the speed of the blade tip greater than the wind speed.

3.2 Advantages of Wind Energy

**Free Fuel:** Unlike other forms of electrical generation where fuel is shipped to a processing plant, wind energy generates electricity at the source of fuel, which is free [6]. Unlike fossil fuels such as coal and oil, which exist in a finite supply and which must be extracted from the earth at great environmental cost, wind turbines harness a boundless supply of kinetic energy in the form of wind [8].

**Supports and Preserves Water Clean:** Wind Turbines produce no particulate emissions that contribute to contamination of water sources, thus wind energy also conserves water resources [6].
Clean air and Negligible Greenhouse Gases: Unlike Other sources of electricity that produce harmful greenhouse gases and other particles. Wind power produces none [8].

Mining & Transportation: Obtaining energy from the wind helps to preserve the environment because there is no need for mining and no need transport resources to a power plant [8].

Land Preservation: Wind turbines are erected over a vast geographic area, but their actual damage on the land is small as the turbines base only covers a small portion on land. It has a minimum impact on the land and animal where they are built.

3.3 Disadvantages of Wind Energy

Shadow Flicker: Shadow flicker occurs when the blades of the rotor cast a shadow as they turn [8]. This results in alternating changes in light intensity appearing to flick on and off. About 3 per cent of people with epilepsy are photosensitive, generally to flicker frequencies between 5-30Hz [9].

Sound and Noise-Low Frequency and infrasound: Wind turbines are not silent, thus the most critical environmental impact of wind turbines is the noise pollution. The sounds they produce are typically foreign to the rural settings where wind turbines are most often used [8]. There are two forms of noise emanated by wind turbines: mechanical and aerodynamic. Even though studies show that infrasound from wind turbine are below the level where known health effects occur, a small increase in sound level at low frequency can result in a large increase in perceived loudness. This may be difficult to ignore, even at relatively low sound pressures, increasing the potential for annoyance [9].
Aesthetics: People have widely varied reactions to seeing wind turbines on the landscape [6]. An overwhelmingly large majority perceives wind energy as highly benign and desirable but most who favor wind energy do not favor wind turbines to be located near them. As wind turbines are made larger and larger to make them more economical and to reduce their carbon footprint per unit energy generated, their dominance on landscapes and the extent of their visibility is also proportionately increasing [7], thus the reaction from the people.

![Figure 3.3.1 Growth in size of commercial wind turbines](image)

Biological Resource Impacts: The construction of wind turbines can impact plants and animals. The impact on the plants and animals depend on the sensitivity of the proposed area of construction. The wildlife impacts can be classified into direct and indirect impacts. The direct impact is the mortality from collisions (especially bats and bird) with wind energy plant while the indirect impacts are avoidance, habitat disruption and displacement [10].

A Variable Resource: Turbines produce electricity only when the wind blows.
3.4 Betz Limit

It indicates the maximum power that can be extracted from the wind, independent of the design of a wind turbine in open flow [13]. The Betz limit was derived by a German physicist who calculated the value. The Betz limit value is stated as 16/27 approximately 0.593, this states that no wind turbine could covert more than 59.3 percent of the kinetic energy of the wind into mechanical energy turning a rotor.

![Betz Criterion](image)

**Figure 3.4.1 Relationship between tip-speed ratio (TSR) and the coefficient of power (C_p) [14]**

3.5 Fundamental Equations of Wind Power

The theoretically available power in the wind can be expressed as:

\[ P_{\text{wind}} = \frac{1}{2} \rho A v^3 \]

Where: \( P_{\text{wind}} \) = power (watts)

\( \rho \) = density of the air (kg/m\(^3\)).

\( A \) = the area the wind is passing through the blade-perpendicular to the wind (m\(^2\)).

\( v \) = velocity of the wind (m/s)
The Power extracted by the wind turbine can be expressed as:

\[ P_{turbine} = \frac{T \cdot 2 \cdot \pi \cdot N}{60} \]

Where: \( P_{turbine} \) = power (watts)

\( T = \) torque (N/m)

\( N = \) rotational speed (rpm)

Power coefficient, \( C_p \), is the ratio of power extracted by the turbine to the total contained in the wind resource.

\[ C_p = \frac{P_{turbine}}{P_{wind}} \]

Where: \( P_{turbine} = \) power extracted by blade (watts)

\( P_{wind} = \) power contained in the wind (watts)

Tip Speed Ratio (TSR): for wind turbines it’s the ratio between the tangential speed of the tip of a blade and the actual velocity of the wind. Tip speed ratio is related to efficiency, this value varies with the design of the blade.

\[ \lambda = \frac{\text{blade tip speed}}{\text{wind speed}} \]

Where: \( \lambda = \) Tip Speed Ratio
The blade tip speed can be calculated as:

\[
\text{blade tip speed} = \frac{N \pi D}{60}
\]

Where: 
- \(N\) = rotational speed (rpm)
- \(D\) = diameter of the turbine (m)

3.6 Spiral Wind Turbine

The spiral wind turbine uses the combination of both principles of lift and drag force to function. This feature makes the small spiral turbine a great choice for urban use. In urban areas the wind speed tend to be irregular and low, and not favorable for conventional turbines. The design applied by the spiral turbine allows it to function in such environment, converting the straightforward movement into a rotating movement. Because the wind direction changes frequently, the design of the turbine uses the drag force, therefore allowing it to automatically yaw to follow the wind. This automatic alignment reduces the cost because it does not employ any extra yawing systems.

3.7 Permanent Magnet Generators

A permanent magnet generator is a perfect choice for small wind turbine applications. This type of generator uses permanent magnets for self-excitation that is made possible without an energy supply, therefore converting mechanical energy to electrical energy efficiently. This type of generator has no winding like the ones found on a typical generator. In this case the windings have been replaced with magnets and have a high efficiency. Permanent magnet generators can generate power at any speed and have a high energy yield. This generator eliminates the need of a gearbox, the losses are further reduced, as well as the maintenance time and costs, while torque and output power per volume unit are usually higher than electromagnetic excited-machines [23]. The generator has a lower temperature, therefore a smaller and simpler cooling system can be used if
need be. The low temperatures also reduces the temperature of the bearings and therefore improves the reliability and the lifetime of the bearings [23] [24]. The most common types of Permanent magnets available are radial flux machines, axial flux machine, and transversal flux machine.

IV. COMPUTATIONAL FLUID DYNAMIC (CFD)

The availability of commercial CFD software has made the analysis of wind turbine more cost effective and time saving. Such software commonly used for this application include STAR-CD, ANSYS FLUENT/CFX, and Autodesk CFD among others. CFD is the science of predicting fluid flow, heat and mass transfer, chemical reactions and related phenomena by using numerical analysis and algorithms to solve the set of governing mathematical equations.

4.1 Computational Fluid Dynamics (CFD) Procedure

Computational Fluid Dynamics software consists of three procedures.

1) **Pre Processing:** This step consists of defining the geometry so as to define the domain of interest. The domain is then divided into sections, called a mesh.

2) **Solver:** At this step the boundary conditions of the problem have already been defined. The problem is then solved using the software of choice. In addition the physics model needed and the numerical method are defined in this step and then the problem is solved.

3) **Post-processing:** At this stage the results are obtain in the form of values. This values are analyzed graphically using line plots, contour plots, streamlines, vectors, or the appropriate representation needed for the problem.
4.2 CFD Method

Most solver are based on the finite volume method. CFD software that use the method include FLUENT, CFX and STAR-CD to name a few. In the method the domain is discretized onto a finite set of control volumes (or cells). The general conservation (transport) equations for mass, momentum, energy among others are solved on this set of control volumes. The partial differential equations used are discretized into a system of algebraic equations which are then solved numerically to render the solution.

![Control Volume](image)

**Figure 4.2.1** Fluid region of pipe flow is discretized into a finite set of control volumes [31].

4.3 Turbulent Models

In computational fluid dynamics, the case of wind turbines is simulated under turbulent flows. Turbulence is unsteady, irregular motion in which transported quantities (mass, momentum, scalar species) fluctuate in time and space.

![Turbulence Structures](image)

**Figure 4.3.1** Turbulence Structures [17]
4.4 Computational Approaches

There are three different types of simulated methods which are: Reynolds-Average Navier-Stoke (RANS) models, Large Eddy Simulation (LES), Detached Eddy Simulation (DES). To theoretically simulate turbulent flow, the computational domain should be large enough to contain biggest eddy. The mesh must also be sufficiently small to find out the smallest eddy.

1) Reynolds-Average Navier-Stoke (RANS) models is the oldest and most common approach turbulence modelling. It is a time-averaged equation of motion for fluid flow. The RANS equation is defined as:

\[
\rho \frac{D U_i}{Dt} = \frac{\partial P}{\partial X_i} + \sum_j \left[ \mu \left( \frac{\partial U_i}{\partial X_j} + \frac{\partial U_j}{\partial X_i} \right) - \rho \bar{u}_i u'_j \right]
\]

The left hand side of this equation represents the change in mean momentum of fluid element. This change is balanced by the mean body force, the isotropic stress owing to the mean pressure field, the viscous stresses, and apparent stress \((-\rho \bar{u}_i u'_j)\) owing to the fluctuating velocity field, generally referred to as the Reynolds stresses. This nonlinear Reynolds stress term requires additional turbulence model to produce a closed RANS equation, and has led to the creation of many different turbulence models [18] [19] [20]. The most common used equation is the Spalart-Allmaras Model. This model is a low-cost RANS model solving for a modified eddy viscosity. When in modified form, the eddy viscosity is easy to resolve near the wall. This model is mainly intended for aerodynamic/turbomachinery applications with mild separation, such as supersonic/transonic flows over airfoils, boundary-layer flows, etc. [17]. The transport equation of Spalart-Allmaras Model can be described as [21]:
\[
\frac{\partial}{\partial t} (\rho \tilde{v}) + \frac{\partial}{\partial x_i} (\rho \tilde{v} u_i) = G_v + \frac{1}{\sigma \tilde{v}} \left[ \frac{\partial}{\partial x_j} \left( \mu + \rho \tilde{v} \right) \frac{\partial \tilde{v}}{\partial x_j} \right] + C_{b2} \rho \left( \frac{\partial \tilde{v}}{\partial x_j} \right)^2 - Y_v + S_v
\]

Where: \( \tilde{v} \) = the turbulent kinematic viscosity

\( G_v \) = the production of turbulent viscosity

\( Y_v \) = the destruction of turbulent viscosity

\( \sigma \tilde{v} \) and \( C_{b2} \) = constants

\( v \) = the molecular kinematic viscosity

\( S_v \) = a user-defined source term.

2) Large Eddy Simulation (LES) is a mathematical model for turbulence and is applied in a wide variety of engineering applications, including combustion, acoustics, and simulations of the atmospheric boundary layer. An implication of Kolmogorov’s (1941) theory of self-similarity is that the large eddies of the flow are dependent on the geometry while the smaller scales more universal. This feature allows to explicitly solve for the large eddies in a calculation and implicitly account for the small eddies by using a sub-grid-scale model. [22]

3) Detached Eddy Simulation is a hybrid technique that attempt to combine the best aspects of RANS and LES methodologies in a single strategy [22]. Near-wall regions where the turbulent length scale is less than the maximum grid dimension are treated in a RANS mode of solution. As the turbulent length scale exceeds the grid dimension, the regions are solved using the LES mode. The generation of the grid is more complicated that RANS
or LES case due to the RANS-LES switch. Detached Eddy Simulation is a non-zonal approach and provides a single smooth velocity field across the RANS and the LES regions of the solution. [21]

### 4.5 Solution Models

Table 4.5.1. Reynolds-Average Navier-Stoke Turbulence Model Description, Behavior and Usage. [21][17]

<table>
<thead>
<tr>
<th>Model</th>
<th>Description, Behavior and Usage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spalart-Allmaras</td>
<td>A single transport equation model solving directly for a modified turbulent viscosity. Designed specifically for aerospace applications involving wall-bounded flows on a fine near-wall mesh. It is economical for large meshes. It performs poorly for 3D flows, free shear flows, flows with strong separation. Suitable for mildly complex (quasi-2D) external/internal flows and boundary layer flows under pressure gradient.</td>
</tr>
<tr>
<td>Standard k–ε</td>
<td>The baseline two-transport-equation model solving for k and ε. Coefficients are empirically derived; valid for fully turbulent flows only. It is Robust and widely used despite the known limitations of the model. Performs poorly for complex flows involving severe pressure gradient, separation, and strong streamline curvature. Suitable for initial iterations, initial screening of alternative designs, and parametric studies.</td>
</tr>
<tr>
<td>RNG k–ε</td>
<td>A variant of the standard k–ε model. Equations and coefficients are analytically derived. Significant changes in the ε equation and improves the ability to model highly strained flows. Additional options aid in predicting swirling and low Reynolds number flows. Suitable for complex shear flows</td>
</tr>
<tr>
<td>Model</td>
<td>Description</td>
</tr>
<tr>
<td>----------------------</td>
<td>---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Realizable k–ε</td>
<td>A variant of the standard k–ε model. Its “realizability” stems from changes that allow certain mathematical constraints to be obeyed which ultimately improves the performance of this model. Offers largely the same benefits and has similar applications as RNG. Possibly more accurate and easier to converge than RNG.</td>
</tr>
<tr>
<td>Standard k–ω</td>
<td>A two-transport-equation model solving for k and ω. It demonstrates superior performance for wall-bounded and low Reynolds number flows. It is suitable for complex shear flows involving rapid strain, moderate swirl, vortices, and locally transitional flows.</td>
</tr>
<tr>
<td>SST k–ω</td>
<td>A variant of the standard k–ω model. Combines the original Wilcox model for use near walls and the standard k–ε model away from walls using a blending function. The transition and shearing options are borrowed from standard k–ω. It is more accurate and reliable for wider class flow that the standard k–ω.</td>
</tr>
<tr>
<td>Reynolds Stress</td>
<td>Reynolds stresses are solved directly using transport equations, avoiding isotropic viscosity assumption of other models. Use for highly swirling flows. It is more accurate than the k–ω model but five additional transport equations in 2D flows and seven additional transport equations in 3D flows means longer CPU time and memory required. Tougher to converge due to close coupling of equations. Suitable for complex 3D flows with strong streamline curvature, strong swirl/rotation.</td>
</tr>
</tbody>
</table>
4.6 Issues with CFD Simulations.

The accuracy of the simulation is affected by the limitations of the software being used. The models provided by the software cannot accurately simulate the turbulence that wind turbines will have when operational. The limitations are also brought about by the computer’s hardware. Finer meshes are required to simulate a full wind turbine, this requires a significant amount memory and thus requiring a computer with high specification. The complexity of the wind turbine also plays a role in the limitations of the simulation because of the turbines complexity, thus a fine mesh may be difficult to apply. Finally, the geometry of the wind turbine blade may vary in size at different points, this may lead a mesh that is difficult to generate and control.

V. SIMULATION SETTINGS FOR CFD ANALYSIS IN FLUENT

ANSYS Workbench 16.0 was used to simulate the wind turbine. The procedure was documented for further studies by any other party.

1. The geometry was imported to ANSYS Design Modeler. The Wind turbine geometry was imported directly from a SolidWorks file. This was feasible because of the support of SolidWorks geometry extension (.SLDPR) in ANSYS.

Figure 5.1 Geometry import
2. The stationary and the rotating area for the simulation were created as illustrated below.

![Figure 5.2 Stationary and rotating area.](image)

3. The 3 Booleans required for this geometry was created at this point. The first Boolean has the rotating air selected as the *target bodies*, the turbine as the *tool bodies* and *preserve tool bodies* was set to no. The second Boolean created has the air hole as the *target bodies*, the rotating air as the *tool bodies* and *preserve tool bodies* was set to yes. The third and final Boolean has the rotating air selected as the *target bodies*, the turbine as the *tool bodies* and *preserve tool bodies* was set to no.

![Figure 5.3 First Boolean](image)  ![Figure 5.4 Second Boolean](image)  ![Figure 5.5 Third Boolean](image)
4. The Two parts left after completing the Booleans were selected and the Details of Solid bodies was changed to fluids.

![Figure 5.6 Details of parts changed to fluid](image)

5. A mesh was generated in this step and the setting were set as follows. Advanced size function to proximity and curvature, relevance center to medium, smoothing to medium, transition to slow and span angle center to fine.

![Figure 5.7 Generated Mesh](image)
6. After the mesh is completed the named selections are created and labeled as shown below.

![Figure 5.8 Wind tunnel](image1.png)  ![Figure 5.9 Blade](image2.png)  ![Figure 5.10 Rotating Air](image3.png)

**Figure 5.8 Wind tunnel**  **Figure 5.9 Blade**  **Figure 5.10 Rotating Air**

7. The setup for FLUENT was opened and in the General section the mesh was checked and the units were set to the required units. In this case angular velocity was set to RPM and pressure to atm. The k–ω- Shear Stress Transport (SST) turbulence model was used to accurately predict the separation of the flow [25].
8. In Cell Zone Condition setup the rotating air options were opened. Frame of motion was checked and the desired rotational velocity was entered.

9. The Boundary Conditions was selected and the inlet and outlet were setup. The inlet was selected, the options were opened and the velocity magnitude was entered. Next the outlet was selected, the options opened and the gauge pressure was set to zero. For both the inlet and outlet the specification method was set to $k-\omega$. The backflow turbulent kinetic energy
and backflow specific dissipation rate were left as the default values provided automatically.

Figure 5.16 Inlet options

Figure 5.17 Outlet options

10. The Solution method that was selected for this simulation is a SIMPLE scheme. The solution initialization method used was Hybrid initialization.

Figure 5.18 Solution Methods

Figure 5.19 Solution initialization
11. After initializing the solution the next step is to click on check case for any warnings, errors or recommendations in the setup for the simulation. If no issues are found proceed with setup. The number of iterations was set and the simulations was then calculated. The results were processed using CFD-Post processing.

![Figure 5.20 Check Case](image1)

![Figure 5.21 Iteration setup and calculation initialization](image2)

VI. IMPLEMENTING 3D PRINTING AS A RAPID PROTOTYPING METHOD

6.1 Rapid Prototyping (RP)

It is a group methods used to fabricate a scale model of a physical part using a computer aided design (CAD) data [26]. Rapid prototyping provides a 3-D visualization of a CAD item. Most of the time the RP part is not the final product because of the material used. RP is suited for complex geometries that are better visualized when a 3-D part is present. This method is used to test the items shape and design before it moves to structural design tests and onwards to mass production.
6.2 Rapid Prototyping Methods

There are several rapid prototyping methods available today. The commercially available and most used methods include: Stereolithography (SLA), Selective Laser Sintering (SLS®), Laminated Object Manufacturing (LOM™), Fused Deposition Modeling (FDM), Solid Ground Curing (SGC), and Ink Jet printing techniques.

1) Stereolithography is a method that creates three dimensional models, in which a computer-controlled moving laser beam is used to build the required model. The model is built up layer by layer from a liquid polymer that hardens on contact with the laser.

2) Selective Laser Sintering (SLS®) is a method that uses a laser to sinter powdered material. The laser is automatically aimed at point in space defined by the 3D model, this binds the material together and creates the desired model [27].

3) Laminated Object Manufacturing (LOM™) this method employs adhesive coated paper, plastics, or metal laminates that are layered and glued and then cut to produce the desired model.

4) Solid Ground Curing (SGC) this method is a photo-polymer additive manufacturing technology that produces model with the use of a high power UV lamp through a mask. The curing is a result of exposing each layer to a UV lamp and the area with the photopolymer hardens [28].

5) Ink Jet printing techniques is a method that employs the technique similar to inkjet printers that deposit tiny droplets of ink onto paper. In this case the ink is replaced with thermoplastics and wax that are kept in a liquid form. These materials are then sprayed to produce a model.
6.3 Three Dimensional (3D) Printing

Three dimensional printing refers to the various methods used to create a three dimensional piece from a computer aided design model. In 3D printing the object is built layer by layer and is controlled by a computer. As a result this method can be used to create complex models that are not possible with conventional methods.

In this project Roland’s monoFab ARM-10 printer with layered projection technology printing was used to create the model. This produces semitransparent models for concept and form testing. This technology uses photo curable resin that hardens when exposed to UV light and a projector with UV LED to print an object [29].

![Figure 6.3.1 Layered projection technology printing](image1)

![Figure 6.3.2 Roland monoFab ARM-10](image2)
VII. PROCEDURE FOR 3D PRINTING

1) The model geometry was created using SolidWorks and after completing the model it was saved as a STL file.

2) Import the STL data using monoFab AM.

3) If there are any errors with the STL data, click Healing to fix them.

![Figure 7.1 Views of imported file](image1)

![Figure 7.2 Geometry Healing](image2)
4) Position the object as required. Move it on the X, Y, and Z axis. Rotate it and adjust the size to make the model fit inside the printing area.

5) Print multiple items at once if desired, generate the supports for the model and adjust the finish of the job. In this case only one model was printed.

![Figure 7.3 Model positioning](image1)

![Figure 7.4 Supports](image2)

6) Install the liquid material vat in the printer. Loosen the liquid material vat retaining screws and insert the vat. Tighten the vat retaining screws.

![Figure 7.5 Loosen screws [29]](image3)

![Figure 7.6 Insert material vat [29]](image4)
7) Adjust the initial printing height (Z0). Using the appropriate tool to loosen the Z0 adjustment screws. On the printing screen under the replace vat option press down. The printing platform descends to the bottom of the liquid material vat.

8) When the printing platform has stopped moving tighten the Z0 adjustment screws, while slightly holding the printing platform down. On the printing screen under the replace vat option press up.
9) Add resin to the liquid material vat and ensure not to fill with resin beyond the full line of the rear side. Also adjust the legs of the printer so as for the resin to collect at the back of the material vat.

10) Check the print data for errors and ensure all setting are as desired.

11) Click on Print button and wait for the job to complete, the estimated time of completion is displayed at the bottom right corner.

12) When the printing is complete loosen the platform retaining screw and pull the printing platform.

![Figure 7.10 loosen platform retaining screw and pull platform](image)

13) Place the printing platform in the work tray and remove the model. Submerge the model in a container with ethanol for about one to two minutes while agitating it. Clean the ethanol off the model when completed.

14) Expose the printed model to sun to completely cure the resin. After curing it, is then safe to remove the supports.

15) The finished model of the spiral turbine can be found in Appendix E.
VIII. RESULTS

![Torque- RPM](image)

**Figure 8.1 Torque for different values of wind velocity**

Figure 8.1 shows the torque against RPM curves for various wind speeds. When the curve reaches its peak torque it gradually decrease, as this happens the RPM increases. As the wind speed increase the value of the torque increase making the turbine revolve faster.

![Power- RPM](image)

**Figure 8.2 Power for different values of wind velocity**
Figure 8.2 shows the Power against RPM curves for different wind speeds. When the turbine reaches the peak power produced it then gradually starts to decrease. The higher the wind speed the more energy it generates.

![Power Coefficient –Tip Speed Ratio](image)

**Figure 8.3 Power Coefficient –Tip Speed Ratio (TSR)**

Figure 8.3 shows the Power Coefficient against the tip speed ratio curves with respect to several air velocities. The maximum power coefficient can be observed to be around 0.297 and it occurs when the tip speed ratio is about 2.06 for all air speeds. From the results the spiral turbine can be observed to be more efficient when compared to the Savonius rotor which has a peak efficiency of 0.16 and the cup vertical axis wind turbine with an efficiency of 0.08 [33]. The spiral turbine is also more efficient than a pure drag type turbine which has a maximum power coefficient of approximately 0.2 [34]. The result show that the turbine has a relatively high rotor efficiency and a high power coefficient value over a wide range of Tip speed ratio.
Figure 8.4 Pressure results at various wind velocities and RPM

Figure 8.4 shows the pressure at different wind velocities for the wind turbine. A pressure difference can be observed on the blade. The highest pressures are found on the areas around the tip, and the low pressure can be found at the back. The resulting pressure difference on the turbine creating a torque. The pressure on the blade can be visualize further on figure 8.5 where the high pressures and low pressures can be observed.
Figure 8.5 Pressure on the blade at various wind velocities and RPM
Figure 8.6 Average velocity at various wind velocities and RPM

The contours shown in figure 8.6 correspond to the average velocity on the wind turbine. The highest velocities were observed in the area around the turbine’s tips. A zone with lower speed was observed inside the turbine as the wind flowed through the turbine. This slowing down is a result of the wind being blocked by the wind turbine. The results also show that there is a region behind the turbine where the wind exits that has a low speed and a circular pattern.
IX. CONCLUSION AND OUTLOOK

A spiral type wind turbine was designed and optimized, with computational fluid dynamics simulations and demonstrated a fairly high power coefficient when compared to other small turbines.

The maximum efficiency for the spiral turbine occurred when the Coefficient of power was at its peak. In this case it was observed at 0.297 (29.7 percent). When compared to Savonius rotor which has a peak efficiency of 0.16 (16 percent), the spiral turbine has an 85.6 percent improvement.

The spiral wind turbine is able to extract an average of 50 percent of the maximum power that can be extracted from the wind according to the Betz Limit (59.3 percent).

According to the results obtained from the analysis the design of the turbine looks promising and the demonstrated potential for small wind turbine applications.

A plastic model of the wind turbine has already been made and physical experimental testing will be carried out to confirm the simulation results.
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Appendix A

Turbine Assembly
Appendix B

Turbine Geometry

![Diagram of a spiral turbine with labeled dimensions R0.5, R80, 45°, 93, Ø100, and R2.](image)
Appendix C

Turbine Geometry
Appendix D

Turbine Isometric Geometry

Spiral Turbine
Appendix E
3D Printed Model
Appendix F
Roland, monoFab ARM-10, Part Names [29]

1) Front Cover
2) Power button
3) Rubber feet (x4 with height adjustment screws)
4) Power cord connector
5) USB connector

1) Z-axis unit (inside red box)
2) Printing platform handle
3) Shutter level
4) UV Irradiation outlet (with shutter)
5) Liquid material vat stopper
6) Printing platform retaining screw
7) Z0 adjustment screw
8) Printing platform
9) Liquid material vat
10) Liquid material vat retaining screws
11) Liquid material vat holder
Appendix G

Roland, monoFab ARM-10, Specification Table [29]

<table>
<thead>
<tr>
<th>Specification</th>
<th>ARM-10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Build technology</td>
<td>Layer projection system</td>
</tr>
<tr>
<td>Build size</td>
<td>130 (W) x 70 (D) x 70 (H) mm, 5.1 (W) x 2.7 (D) x 2.7 (H) inches (Job volume of resin is up to 300 g (0.7 lbs))</td>
</tr>
<tr>
<td>Build speed</td>
<td>10 mm/h (Layer pitch = 0.15 mm)</td>
</tr>
<tr>
<td>Light source</td>
<td>UV-LED (ultraviolet light emitting diode)</td>
</tr>
<tr>
<td>XY resolution</td>
<td>0.2 mm</td>
</tr>
<tr>
<td>Z axis resolution</td>
<td>0.01 mm</td>
</tr>
<tr>
<td>Power</td>
<td>Machine: DC 24V, 0.6 A</td>
</tr>
<tr>
<td></td>
<td>Dedicated AC adapter: AC 100 V to 240 V +/- 10%, 50/60 Hz</td>
</tr>
<tr>
<td>Power consumption</td>
<td>15 W</td>
</tr>
<tr>
<td>Acoustic noise level</td>
<td>During operation: 55 dB (A) or less</td>
</tr>
<tr>
<td></td>
<td>During stand-by: 49 dB (A) or less</td>
</tr>
<tr>
<td>Dimensions</td>
<td>430 (W) x 365 (D) x 450 (H) mm, 17.0 (W) x 14.4 (D) x 17.8 (H) inches</td>
</tr>
<tr>
<td>Weight</td>
<td>17 kg, 37.5 lbs</td>
</tr>
<tr>
<td>Interface</td>
<td>USB</td>
</tr>
<tr>
<td>Installation environment</td>
<td>During operation: Temperature of 20 to 30℃, 65 to 85% relative humidity (no condensation)</td>
</tr>
<tr>
<td></td>
<td>Not operating: Temperature of 5 to 40℃, 41 to 95% relative humidity (no condensation)</td>
</tr>
<tr>
<td>Accessories</td>
<td>AC adapter, Power cord, USB cable, Liquid material vat, Printing and washing tools (Metallic spatula, Plastic spatula, Tweezers, Washing container x 2, Hexagonal wrench, Spanner, Rubber gloves, Work tray, etc.), Start-up page information card, Read this first (Booklet),</td>
</tr>
<tr>
<td>Supplies (sold separately)</td>
<td>Resin (350 g bottle), Liquid material vat</td>
</tr>
</tbody>
</table>

Appendix H

Roland, monoFab ARM-10, Dimensional drawing [29]