



DESIGN AND ANALYSIS OF 5 KW SAVONIUS ROTOR BLADE

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ABSTRACT

This paper presents the design and analysis of the Savonius rotor blade to generate 5 kW power output. The relevant design parameters and theories were studied in this paper and used to determine related design geometry and requirements of the Savonius rotor blade. The Savonius rotor was designed with the rotor diameter of 3.5 m and the rotor height of 7 m. The 3D model of Savonius rotor blade was created by using SolidWorks software. Computational Fluid Dynamics (CFD) analysis and structural Finite Element Analysis (FEA) are presented in this paper. CFD analysis was performed to obtain the pressure difference between concave and convex region of the blade while FEA was done to obtain the structural response of the blade due to the wind load applied in term of stresses and its displacements.

Keywords: Savonius, Rotor Blade, CFD, FEA.

1.0 INTRODUCTION

The developments of renewable energy especially wind energy become widely since 1973 due to the oil crisis issues. This view has been supported by Peter *et al.*, (2008) who states that the oil price is forecasted to be raised in the future and thus wind energy is an alternative energy sources. The wind turbine is a device that utilizes wind energy to generate mechanical or electrical power. According to Manwell *et al.*, (2009), there are two types of wind turbine: Horizontal Axis Wind Turbine (HAWT) and Vertical Axis Wind Turbine (VAWT). HAWT are most commonly known type of wind turbine and it operates parallel to the direction of the wind whereas VAWT rotor is operated perpendicular to the direction of wind. The two most common design principle of VAWT is Savonius type and Darrieus type.

The paper focuses on the Savonius type rotor blades design and analysis. Savonius type rotor blade is a simple wind turbine that operates based on drag concept. According to Akwa *et al.*, (2011) Savonius rotor can be designed with two or three blades, in single stage or multi-stages. The working principle of Savonius rotor is resembled to a cup anemometer. The low efficiency of VAWT limited its use in large power production. However, VAWT has several advantages over HAWT that make it widely use in another sector such as water pumping system. The most apparent advantage of VAWT is it can operate in all wind direction and thus are built without using any yaw mechanism (Halsey, 2011). Other advantages included low noise and simplicity.

In this project, a VAWT is designed to produce 5 kW power output. As the performance of VAWT is relatively low, it becomes necessary to explore the effect of number of blades and sizing of the rotor blades in the design stage. The Savonius wind turbine is a drag type VAWT where utilizes the drag force for its operation. D'Alessandro *et al.*, (2009) highlighted that the aerodynamic theories developed for lift type wind turbine (HAWT and Darrieus wind turbine) cannot be applied for Savonius rotor. According to Islam *et al.*, (2005) the flow pattern around the Savonius rotor blade is characterized by flow phenomena that produce pressure differences between the concave and convex surfaces of the blades which will induce to aerodynamic force and torque. Islam *et al.*, (2005) further explained that the feature of flow phenomena including high turbulence, unsteadiness and flow separation. Figure 1 shows the normal drag force, F_N acts perpendicular on the blade surface whereas tangential drag force, F_T acts along tangential direction on each blade. Both F_N and F_T equations have been stated by Islam *et al.*, (2005) as follow:

$$F_N = \Delta P S \sin \theta \quad (1)$$

$$F_T = \Delta P S \cos \theta \quad (2)$$

Where the ΔP represents the pressure difference between the concave and convex surfaces of the blade and the S represent the chord length.

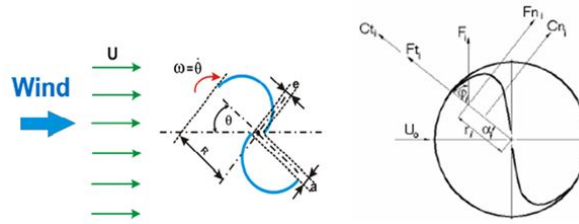


Figure 1: Forces acting on a blade of two blades Savonius rotor, (Islam *et al.*, 2005).

2.0 THEORY AND DESIGN

Wind power, P_w is defined as the multiplication of mass flow rate, ρAV and the kinetic energy per unit mass, $\frac{1}{2} V^2$ (Musgrove, 2010). The wind power is denoted by the equation of:

$$P_w = \frac{1}{2} \rho AV^2 \quad (3)$$

Hayashi, *et al.* (2004) found that the swept area for Savonius Wind Turbine is calculated by multiplication of rotor diameter, D and the rotor height, H . The larger the swept area, the larger the power generated.

$$A = D.H \quad (4)$$

The wind power in Equation (3) represents the ideal power of a wind turbine, as in case of no aerodynamic or other losses during the energy conversion processes. However, as stated by Manwell *et al.*, (2009) there is not possible for all energy being converted into useful energy. The ideal efficiency of a wind turbine is known as Betz limit. According to the Betz limit, as supported by Musgrove (2010) there is at most only 59.3 % of the wind power can be converted into useful power. Some of the energy may lose in gearbox, bearings, generator, transmission and others (Jain, 2011). The maximum power coefficient, C_p for Savonius rotor is 0.30. Hence, the C_p value used in this project is 0.30 and the power output, P with considering the power efficiency is:

$$P = 0.15 \rho AV^2 \quad (5)$$

Wind speed is the major element that affects the power output. The three wind speed parameters involve in this project is cut-in speed, rated wind speed and cut-out speed. Jain (2011) stated that the three wind speed parameters related to the power performance are as follow:

$$V_{cut-in} = 0.5 V_{avg} \quad (6)$$

$$V_{Rated} = 1.5 V_{avg} \quad (7)$$

$$V_{cut-out} = 3.0 V_{avg} \quad (8)$$

All these parameters depend on the value of average wind speed. The average wind speed, V_{avg} was found at 7 m/s. Table 1 summarizes the value of these three wind speed parameters.

Table 1: Value of cut-in speed, rated wind speed, and cut-out speed.

Wind Speed Parameter	Equation	Calculation
Cut-in speed, V_{cut-in}	$V_{cut-in} = 0.5 V_{avg}$	3.5 m/s
Rated wind speed, V_{Rated}	$V_{Rated} = 1.5 V_{avg}$	10.5 m/s
Cut-out speed, $V_{cut-out}$	$V_{cut-out} = 3 V_{avg}$	21 m/s

Aspect ratio is a crucial criterion to evaluate the aerodynamic performance of Savonius rotor. Johnson (1998) suggests the Savonius rotor is designed with rotor height twice of rotor diameter and this lead to better stability with proper efficiencies.

$$AR = H/D \quad (9)$$

Tip speed ratio, λ is defined as the ratio of the linear speed of rotor blade $\omega.R$ to the undisturbed wind speed, V (Solanki, 2009). ω is the angular velocity and R represent the radius revolving part of the turbine. The maximum tip speed ratio that Savonius rotor can reach is 1. Manwell *et al.*, (2009) write that high tip speed ratio

improves the performance of wind turbine and this could be obtained by increasing the rotational rate of the rotor.

$$\lambda = \omega.R/V \quad (10)$$

According to Manwell *et al.*, (2009) solidity is related to tip speed ratio. A high tip speed ratio will result in a low solidity. Musgrove (2010) defines solidity as the ratio of blade area to the turbine rotor swept area. For VAWT, the solidity is defined as

$$\sigma = nd/R \quad (11)$$

Where n is the number of blades, d is the chord length or can be defined as the diameter of each half cylinder, and R is radius of wind turbine. Many researchers have proved that the higher the number of blades, the higher the performance of most wind turbine. However, Saha *et al.*, (2008) and Zhao *et al.*, (2009) found that the two-bladed Savonius rotor has higher performance than three-bladed Savonius rotor. Referring to Saha then the two-blade rotor has been chosen for this project. Table 2 shows the design parameters used in this research.

Table 2: Summary of design parameters.

Parameter	Value
Power Generated	5 kW
Swept Area	23.5 m ²
Rated Wind Speed	10.5 m/sec
Aspect Ratio	2
Tip Speed Ratio	1.0
Solidity	2.114
Diameter – Height	3.5 m – 7 m
Number of Blade	2

The design of the Savonius rotor blade is shown in Figure 2, while Table 3 shown the detail dimension of the Savonius rotor blade. The material proposed for the Savonius rotor blade in this paper is E-glass fiber. Since the manufacturing process and material cost are not considered in this paper, the material is chosen based on the material properties. Table 3 summarizes the general properties of the E-glass fiber and also rotor blade for this research.

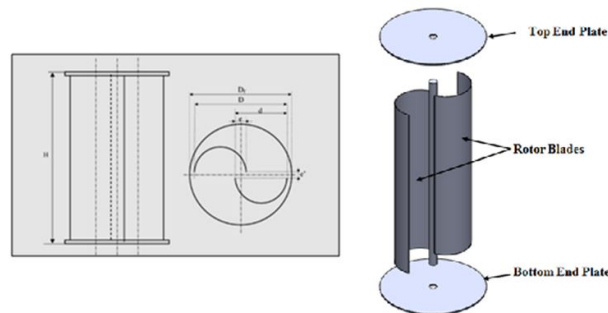


Figure 2: Design of Savonius rotor blade.

Table 3: Summaries of rotor blade design and the material properties of E-glass fiber.

Parameter	Value
Swept Area, A	23.5 m ²
Rotor Diameter, D	3500 mm
Rotor Height, H	7000 mm
End Plate Diameter, D_r	3850 mm
Chord Length, d	1850 mm
Overlap Distance, e	200 mm
Blade Thickness, t	10 mm
End Plate Thickness, t_r	50 mm
Density	1.7e ³ – 2e ³ kg/m ³
Young's modulus	27.2 – 39.4 GPa
Poisson's ratio	0.07 – 0.11
Tensile strength	217 – 520 Mpa
Compressive strength	276 – 460 MPa

3.0 SIMULATION AND ANALYSIS

In this paper, two kinds of simulation and analysis were done i.e. Computational Fluid Dynamics (CFD) Analysis and Structural Analysis by using SolidWorks Flow Simulation and SolidWorks Structural Simulation/Cosmo.

3.1 Computational Fluid Dynamics (CFD) Analysis

The purpose of this simulation is to obtain the pressure different between the concave and convex surface. The pressure difference between the concave and convex blade surface of the Savonius rotor induced drag force that turns the blade. The pressure difference was obtained by implementing Computational Fluid Dynamics (CFD) analysis on SolidWorks Flow Simulation. The two flow types in this paper were external flow and internal flow analysis. Both analyses were static analysis.

The engineering goals for the internal analysis and the external analysis are two Surface Goals and four Global Goals. The two Surface Goals are dealing with total pressure, for both concave and convex surface. The four Global Goals are deal with total pressure, velocity, normal force and force.

3.1.1 External flow analysis

The flow type of Savonius rotor blade is considered as external flow since it involves a solid model which is fully surrounded by the flow. The fluid flow is not bounded by outer surface, but bounded only by the Computational Domain boundaries. The Computational Domain is firstly defined to 7m x 7m x 9 m, which means that the Savonius rotor is enclosed by this region and the volume is fixed within this fluid flow field as shown in Figure 3. The Computational Domain can be set in different size, however, the bigger the Computational Domain, the longer the meshing and solution time.

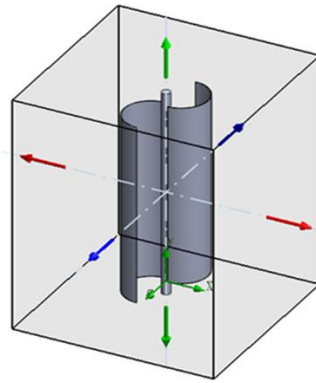


Figure 3: Computational domain for Savonius rotor in external flow analysis.

After the input data is ready, the model then is entering the meshing process. The meshing is viewed through a cut plot as shown in Figure 4 (a). The fluid is experienced separation when it passes through the blade and this region is considered as high-gradient flow region. The mesh control is set to be finer in this region to obtain better solution accuracy.

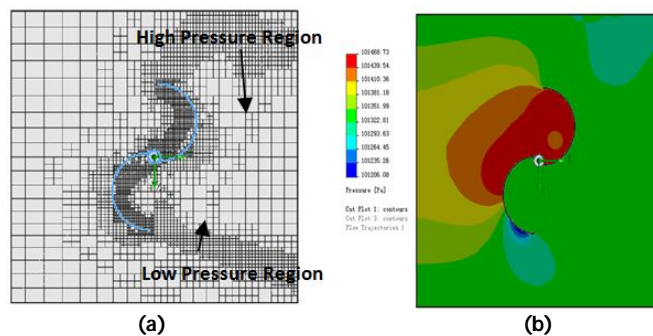


Figure 4: External flow distribution (a) Meshing and (b) pressure.

The pressure distribution around the Savonius rotor is viewed by a contour cut plot from the top view. The contour cut plot display the higher pressure region and lower pressure region as red and blue color respectively. From Figure 4(b), the pressure is high near the concave surface and is low near the convex surface. The maximum and minimum pressures are 101.469 kPa and 101.206 kPa respectively. The flow pattern is viewed by a flow trajectory is shown in Figure 5.

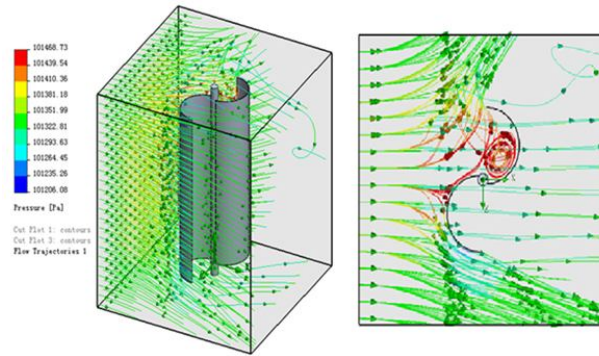


Figure 5: Flow pattern of external flow (ISO view and top view).

3.1.2 Internal flow analysis

In this analysis, the wind enters the wind tunnel with the size of 10m x 25m x 8m, flow through the Savonius rotor blade, and then exits through the outlet that is set to environmental conditions. The Savonius rotor blade is placed in the middle of wind tunnel. In internal analysis, the Computational Domain is automatically enveloped the model wall, which is the wind tunnel size for this paper. The lids are used to apply boundary conditions which introduce to inlet velocity and outlet condition as shown in Figure 6. The lid thickness for an internal analysis is usually not important for the analysis. However, the lid should not be so thick until the flow pattern is affected downstream in some way. If the lid is created to be too thin, this will make the number of cells to be very high. For most cases the lid thickness could be the same thickness used to create the neighboring wall (Dassault System, 2011).

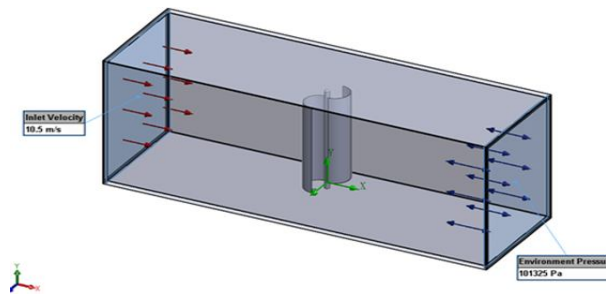


Figure 6: Setup boundary condition for internal flow analysis.

Figure 7 shows the meshing of the model and pressure distribution along the wind tunnel, observed from the top. The maximum pressure is indicated by the red color region whereas the minimum pressure is in the blue color region. Figure 7 also shows that the concave surface experience higher pressure than convex surface. The maximum and minimum pressure found in this analysis are 101.511 kPa and 101.189 kPa respectively. The flow trajectory pattern of the internal flow analysis is shown in the Figure 8.

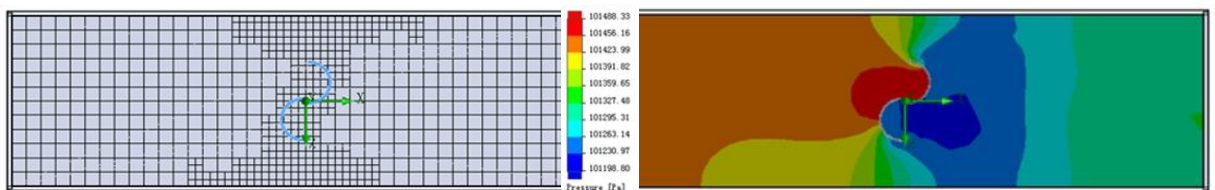


Figure 7: Meshing and pressure distribution result of the internal flow.

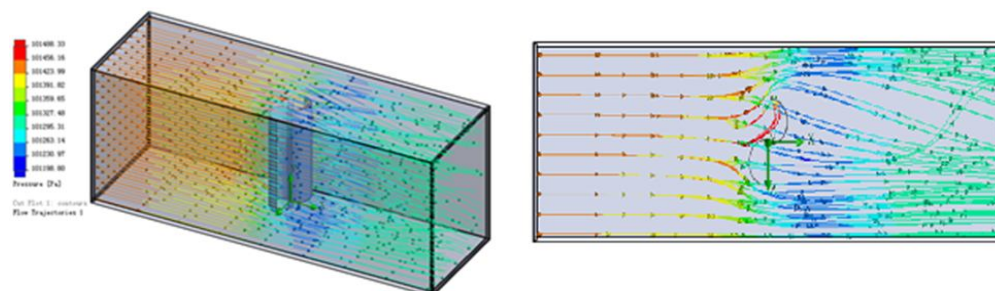


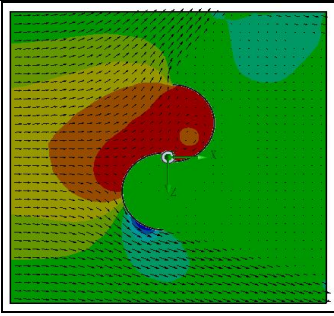
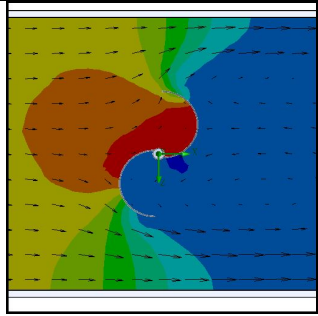
Figure 8: Flow pattern of internal flow (ISO view and top view).

3.1.3 Comparison of external and internal flow analysis

Both external and internal flow analysis shows different results. From the view of pressure distribution, both analyses have shown that the pressure is higher on the concave surface and lower on the convex surface. This has verified the research statement by Sargolzaei and Kianifar (2007). However, the pressure differences of both analyses are not same. Internal flow analysis has higher pressure differences than external flow analysis, which are 322.15 Pa and 262.65 Pa respectively. This explained by the velocity vector in Figure 4 and Figure 7.

Since the Savonius rotor was set at static position, when the wind reached on the blade, it was not turn as in real world condition and hence blocked the wind flow. From Figure 4, the velocity vector plot shows that the wind which blocked by the Savonius rotor blade are tend to flow in the direction that bias from the wind flow in the external flow analysis. The wind was not completely flow through the rotor blades. However, the wind was completely passed through the Savonius rotor blades as shown in Figure 7. This is because the Savonius rotor is bounded by the wind tunnel wall. The air which blocked by the blade is reflected to the wind tunnel wall and then passes through the Savonius rotor blades. Hence, in the static analysis, the result of internal flow analysis is more accurate and precise. Table 4 shows the comparison summary of the external and internal flow analysis.

Table 4: Comparison of external and internal flow analysis.

Aspect	External Flow Analysis	Internal Flow Analysis
Pressure Differences	262.15 Pa	322.15 Pa
High Pressure Region	Concave surface	Concave surface
Low Pressure Region	Convex surface	Convex surface
Vector Plot		
Flow Pattern	The wind flow is blocked by the Savonius rotor blades and bias from the wind direction. Since there is no wall boundary, the wind flow out from the Computational Domain. The wind is not completely flow through the rotor blades.	The wind flow is blocked by the Savonius rotor blades and bias. However, the Savonius rotor is bounded by the wall of wind tunnel. Hence, the wind is completely flow through the rotor blades.

3.2 Structural Analysis

The structure of the Savonius rotor blade is analyzed using FEA static method by SolidWorks Simulation/Cosmo software. Since the two Savonius rotor blades are symmetry, the analysis is performed only on one blade. The FEA result is interpreted in three criteria: stress, deformation, and factor of safety. First step of FEA analysis is assigned material to the blade model where E-glass fiber was the material chosen. Then the fixed constraints/ fixtures are applied on the top, bottom and center of the shaft, as shown in Figure 9. The fixtures constrained all translational and all rotational degrees of freedom. Therefore, the blade is stay in a static and fixed position. The load for this analysis is force with 595.98 N obtained from the aerodynamic analysis and equally distributed on the concave blade surface.

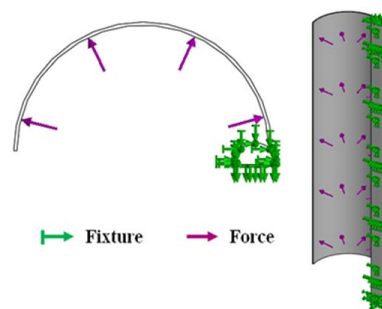


Figure 9: Boundary condition of the rotor blade.

Figure 10 shows the meshing of the model by using tetrahedral shape mesh elements and also depicts the FEA result of the model which presents the stress distribution over the rotor blade structure.

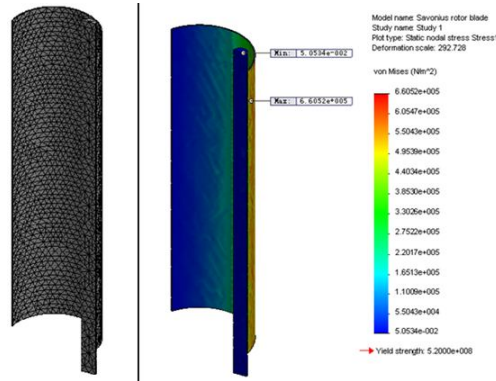


Figure 10: Meshing and stress distribution of the rotor blade.

The maximum and minimum Von Mises stress for the Savonius rotor blade are 6.6052×10^5 Pa and 5.0534×10^{-2} Pa respectively. The result is acceptable because the maximum Von Mises stress is much lower than the yield strength of the material and provide the minimum Factor of Safety as 787.26. Figure 11 shows the deformation of the model under the given load, the maximum displacement is 2.94 mm at the edge of the blade. The deformation is acceptable because it is small in relation to the overall size of the blade structure.

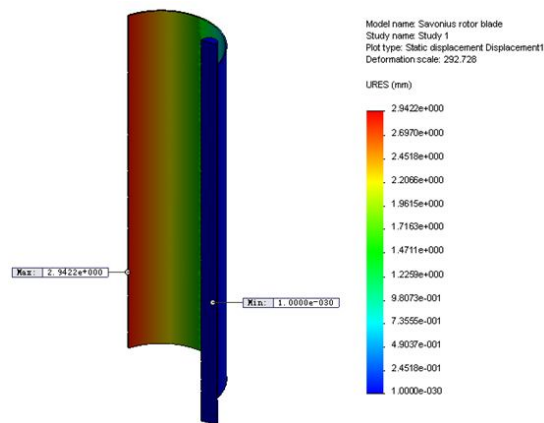


Figure 11: Deformation of the rotor blade.

4.0 CONCLUSION

The paper has investigated the elements that contribute to the design and analysis Savonius rotor blade. The blade was design by using SolidWorks software. CFD analysis was performed in order to obtain the pressure different between the concave and convex surface of the rotor blade. The force induced to the blade was calculated from aerodynamic analysis. The structural feasibility was analyzed by Finite Element Analysis method to obtained the maximum deformation and stress experienced by the rotor blade.

From the CFD analysis, it is found that the concave blade region experience high pressure while the convex blade region experience low pressure for two blades Savonius rotor. The maximum pressure and minimum pressure from internal flow analysis were 101.511 kPa and 101.189 kPa respectively. The high pressure region produces 595.98 N of drag force that spinning the Savonius wind turbine.

The maximum deformation of the Savonius rotor blade was 2.94 mm. This deformation is acceptable because it is relatively small compared to the whole blade model. The maximum Von Mises stress obtained from the FEA was 6.6052×10^5 Pa with the minimum Factor of Safety was 787.26. This concluded that the Savonius rotor blade was safe enough to withstand the aerodynamic force on the turbine.

The presented study was limited by the software and computer capability. In real world condition, when the air flows through the blade, it will induce a force to turn the rotor blade. However, the SolidWorks software is unable to perform the CFD analysis while the blades are turning (dynamic condition). Therefore, only the static CFD analysis was performed in this paper, for both external and internal flow analysis.

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