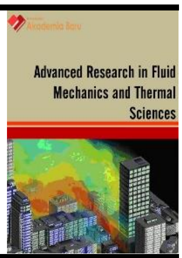
Penerbit Akademia Baru

Journal of Advanced Research in Fluid Mechanics and Thermal Sciences

Journal homepage: www.akademiabaru.com/arfmts.html
ISSN: 2289-7879



Conceptual Design and Structure Analysis of Savonius Vertical Axis Wind Turbine under Low Wind Speed

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Mohamed Saiful Firdaus Hussin[1,4,*], Ridhwan Jumaidin[1,4], Nursabillilah Mohd Ali[2,5], Muhammad Ashraf Fauzi[6], Shahrizal Saat[3,5], Amirul Syafiq Sadun[8], Halyani Mohd Yassim[3,7], Emy Zairah Ahmad[3,7]

[1] Faculty of Mechanical & Manufacturing Engineering Technology, Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia
[2] Faculty of Electrical Engineering, Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia
[3] Faculty of Electrical & Electronics Engineering Technology, Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia
[4] Centre for Advanced Research on Energy, Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia
[5] Centre for Telecommunication Research and Innovation, Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia
[6] Centre for Foundation Studies, Universiti Islam Antarabangsa, 26300 Gambang, Pahang, Malaysia
[7] Centre for Robotics and Industrial Automation, Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia
[8] Faculty of Engineering Technology, Universiti Tun Hussein Onn, 86400 Parit Raja, Johor, Malaysia

ARTICLE INFO

Article history:
Received 6 November 2019
Received in revised form 16 April 2020
Accepted 23 April 2020
Available online 27 May 2020

Keywords:
Savonius Blade; Low Wind Speed; Pugh Method; Topology Optimization

ABSTRACT

This research aims to investigate the stress distribution of Savonius type vertical axis wind turbine subjected to different wind speeds and different penetration positions. This research work involves applying 12 different wind speeds to the design generated from Pugh Method. The wind energies were applied to two positions, which were the edge of blade and uniformly distributed throughout the surface of the blade. SolidWorks 2015 software was used to draw the design of Savonius type vertical axis wind turbine. The drawing was imported to Inspire 2017 for analysis. The analysis is conducted to determine the stress distribution of the blade as wind energy applied to the blade. The results showed that the stress was higher in the area near to the rotor. The results also showed that the maximum displacement, maximum tension/compression stress, maximum shear stress, maximum von Mises stress, and maximum major principal stress of the blade increased as the force or pressure applied increased.

1. Introduction

The issues of global warming due to the combustion of fossil fuels have become critical and by time, the fossil fuel resources will become limited. Hence, there are many types of renewable energy that had been discovered until now to replace fossil fuels, which include wind energy, solar energy,

* *Corresponding author.*
E-mail address: mohamed.saiful@utem.edu.my (Mohamed Saiful Firdaus Hussin)

https://doi.org/10.37934/arfmts.71.2.178187

biomass etc. Besides that, it is the cheapest type of renewable energy and it is clean. It also does not cause pollution like the combustion of fossil fuels which emit unwanted gas. The importance of wind energy had been acknowledged by peoples for a long time [1-2]. Wind energy had been used by peoples as a power to navigate the sailboats for thousands of years. Besides that, the wind energy also had been used as an alternative to pump water and grind grain. The innovation of Poul La Cour after Charles Brush was a success in 1891 to 1918 and this innovation has helped rural areas in Denmark to provide electricity [3]. The success of this innovation has been extensively using and improve until now. The wind turbine can be generally classified into two types based on its rotation axis, which are Horizontal Axis Wind Turbine (HAWT) [4] and Vertical Axis Wind Turbine (VAWT) [5-7]. A HAWT has a horizontal rotor shaft and its generator and components are located at the top of the tower. However, a VAWT has a vertical rotor shaft which different from HAWT and its rotor and components are located at the bottom. The VAWT has more advantages compare to HAWT as it can receive wind from any direction not like HAWT only can receive wind from the front of the rotor [8]. VAWT also able to operate even in low wind speeds area and easier for maintenance since its generator and components is located at the bottom. Besides that, the size of VAWT is smaller than a HAWT which more suitable to be installed in residential areas. The VAWT can be further divided into many types based on their designs.

The three major types of VAWT that often employed are the Savonius type, Darrieus type, and Giromill type. Savonius type VAWT was invented by a Finnish scientist, S. J. Savonius in 1922 which is basically consist of two half-cylinder which attach to the rotor and form a S-shape blade from top view [9] The design of Savonius type VAWT is shown in Figure 1 Darrieus type VAWT was invented by a French engineer, G. J. M. Darrieus in 1931 which has two or three narrow curved blade that surround the rotor [10]. The design of Darrieus type VAWT is shown in Figure 2. However, Giromill type VAWT has been included in the Darrieus's patent which also known as H-rotor which has few straight blades that attached to the rotor by horizontal support [11]. The design of Giromill type VAWT is shown in Figure 3. Although VAWT is able to operate at low wind speed, however, the efficiency of power generation is lower compared to HAWT. Hence, the VAWT will be analyzed in this study in order to enhance the efficiency of power generation. Among many types of VAWT, only the Savonius type VAWT will be the focus in this study. However, the generator available is a high torque generator which needs wind energy with higher speed to initiate the rotation. When wind energy with high speed is applied to the blade of a wind turbine, the stress experienced over the blade which receiving the wind energy may exceed the maximum stress of the blade can withstand [12]. This investigation will focus on designing the concept of Giromill VAWTs, analyzing its displacement and stress distribution based on corresponding wind speed and optimizing the blade design in terms of material usage topologically.

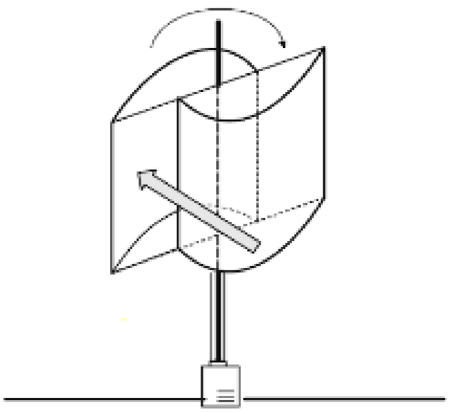


Fig. 1. Savonius type VAWT [11]

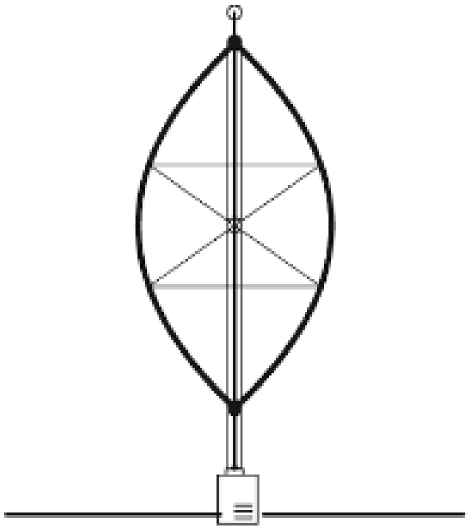


Fig. 2. Darrieus type VAWT [11]

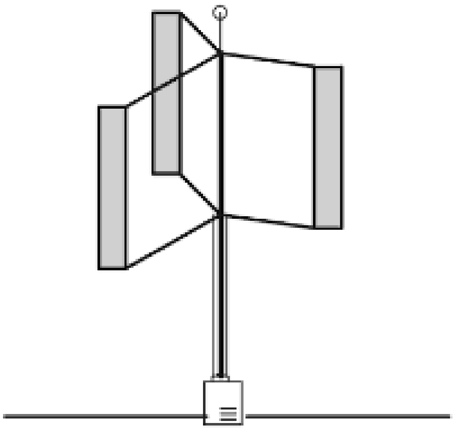


Fig. 3. Giromill type VAWT [11]

2. Methodology

The first phase was about the conceptual design of the Savonius type wind turbine. In this stage, the house of quality was used to determine the problems of available Savonius type wind turbine in market faced and suggest a solution to the problems. Then, the morphological chart was constructed to develop different combinations of ideas. After house of quality and the morphological chart had been constructed, the evaluations were conducted to each alternative generated to determine the alternatives were suitable to be used or not. After the alternatives were evaluated, the best alternative was chosen using the Pugh method [13-14].

The second phase of this research has involved the analysis and optimization. In this stage, the alternative chosen will be analyzed using different wind speeds to determine the displacement and stress distribution of the blade as an effect of the wind energy applied [15]. After the stress distribution over the blade is obtained, the blade will be optimized through topology optimization. The analysis and optimization will be carried out to the design generated from conceptual design. The analysis was assisted by solidThinking software which the design is tested with wind speed in the range of 0-24 m/s. The wind speed is converted to wind force in Newton or wind pressure in Pascal using the formula below

$$P = \frac{1}{2}\rho v^2 \quad (1)$$

where the density of air, ρ and wind velocity, v were taken as 1.225 kg/m^3 and 2 m/s respectively. The force of wind energy applied to the edges of blades is calculated by assuming the surface area 3 cm times the length along edges as below

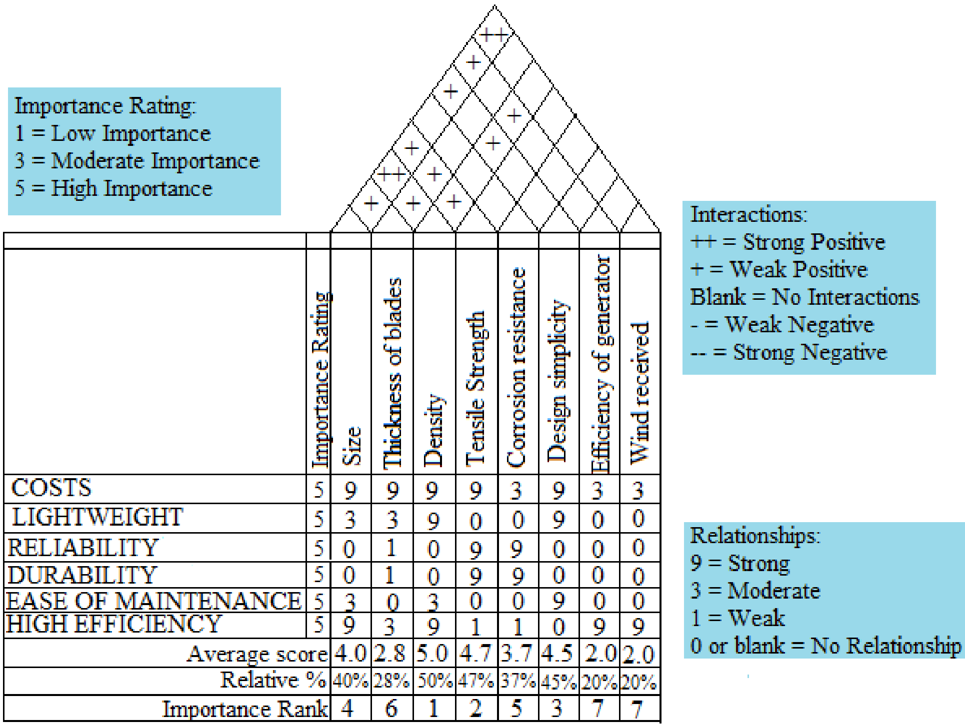
$$F = \frac{1}{2}\left(\frac{1.225\text{kg}}{m^3}\right)(2m/s)^2(0.03m \; x \; 0.2m) = 0.0147 \; N$$

and the pressure is

$$P = \frac{1}{2}\left(\frac{1.225\text{kg}}{m^3}\right)(2m/s)^2 = 2.45 \; Pa$$

3. Results

Figure 4 shows the House of Quality for the Savonius type wind turbine. The House of Quality shows the relationship between the customer requirements and engineering characteristics. There are six customer requirements to be discussed which are costs, lightweight, reliability, durability, ease of maintenance, and high efficiency. There are also 8 engineering characteristics which are size, the thickness of blades, density, tensile strength, corrosion resistance, design simplicity, the efficiency of generator, and wind received. The relationship between customer requirements and engineering characteristics are implicated by using number 9, 3, 1, and 0 which represent the strong relationship, moderate relationship, weak relationship, and no relationship respectively. The first customer requirement is the cost of the wind turbine. The relationship between the cost of the wind turbine and engineering characteristics is the strongest compared to other customer requirements. The cost of the wind turbine is most influenced by the size, thickness of blades, density, tensile strength, and design simplicity. This means that when the engineering characteristics are larger or higher, the cost of the wind turbine will be higher. The cost of wind turbine also moderately related to corrosion resistance, the efficiency of generator, and wind received. This means that producing low-cost wind turbine is the most important thing to be considered. The second customer requirement is a lightweight wind turbine. The engineering characteristics that strongly related to this customer requirement are density, and design simplicity. The lightweight wind turbine also moderately related with the size and thickness of blades. There are two customer requirements that are strongly related to the tensile strength, and corrosion resistance, which is reliability, and durability. This two customer requirement also have weak relationships with the thickness of blades. Next, the ease of maintenance also important in producing a wind turbine, the ease of maintenance is strongly related with the design simplicity. This customer requirement is also moderately related with size and density. The last customer requirement is high efficiency. This customer requirement is strongly related with size, density, the efficiency of generator, and wind received. This customer requirement also has a moderate relationship with the thickness of blades and weak relationships with tensile strength, and corrosion resistance. The most important engineering requirement in this house of quality is density with an average score of 5.0, followed by tensile strength with an average score of 4.7, design simplicity with an average score of 4.5, and size with an average score of 4.0. These engineering characteristics are the objectives of this project.



	Importance Rating	Size	Thickness of blades	Density	Tensile Strength	Corrosion resistance	Design simplicity	Efficiency of generator	Wind received
COSTS	5	9	9	9	9	3	9	3	3
LIGHTWEIGHT	5	3	3	9	0	0	9	0	0
RELIABILITY	5	0	1	0	9	9	0	0	0
DURABILITY	5	0	1	0	9	9	0	0	0
EASE OF MAINTENANCE	5	3	0	3	0	0	9	0	0
HIGH EFFICIENCY	5	9	3	9	1	1	0	9	9
Average score		4.0	2.8	5.0	4.7	3.7	4.5	2.0	2.0
Relative %		40%	28%	50%	47%	37%	45%	20%	20%
Importance Rank		4	6	1	2	5	3	7	7

Fig. 4. House of quality

Table 1 shows the morphological chart of Savonius type wind turbine. In this morphological chart, there are four parameters discussed, which include the design of blade, the material used, the method of blades attach to the rotor, and diameter of the wind turbine. The possible solutions are given based on the most important engineering requirements that listed in House of Quality, which are density, tensile strength, design simplicity, and size. There are four type designs of blades suggested in this morphological chart, which are the curved blade, half-cylinder blade, half-cylinder with middle support blades, and helical blades. All of the designs suggested are simple and easy to manufacture. There are 4 types of material suggested include polypropylene, polycarbonate, CFRP, and GFRP. All the materials suggested are equipped with properties of low density and high tensile strength. The suggested methods for blades attach to the rotor have four types, which are permanently mounted, slide-in, bolts and nuts, and rivets. While for the diameter of the wind turbine, the suggested dimensions are 20cm, 25cm, 30cm, and 35cm. All possible solutions can be combined to form 256 different types of combinations of Savonius type wind turbine.

Table 2 shows the decision matrix of Pugh Method. The 5 concepts with different combinations of solutions had been chosen from the morphological chart for comparison using the decision matrix of Pugh Method. There are 5 parameters that used to compare each concept, which are density, cost, strength, design simplicity, and ease of maintenance. In this decision matrix, concept A is set as a DATUM, while the concepts B, C, D, and E are compared to the DATUM. The DATUM is a Savonius type wind turbine that has a half-cylinder blade design that manufactured using CFRP, the blades are permanently welded to the rotor, and has a diameter of 20cm. Concept B is a Savonius type wind turbine with a curved blade design that manufactured with polypropylene, the blades are attached to the rotor with the slide-in method, and has a diameter of 25cm. Concept B obtains four + signs from density, cost, design simplicity, and ease of maintenance fields. The material used in concept B has lower density and cost compared to DATUM. Besides that, the design of blade of concept B is simpler compared to DATUM. Concept B also applied the slide-in method that easier for maintenance. However, concept B obtains a – sign from the field of strength. The strength of the material used in concept B is lower than DATUM.

Concept C is a Savonius type wind turbine with helical blade design that manufactured with CFRP, the blades are permanently welded to the rotor, and has a diameter of 30cm. Concept C obtains only one - sign from the field of design simplicity. The design of the blade of concept C is more complex compared to DATUM. Besides that, concept C obtains four 0 signs from the fields of density, cost, strength, and ease of maintenance. The material used in concept C has the same density, cost, and strength. The method of blades attach to the rotor is also the same. The concept C obtains a total of one - sign, and four 0 sign. Next, Concept D is a Savonius type wind turbine with half-cylinder with middle support blade design that manufactured with GFRP, the blades are attached to the rotor with bolts and nuts, and has a diameter of 35cm. Concept D obtains two + signs from fields of cost, and ease of maintenance. The material used in concept D has a lower cost compared to DATUM. Besides that, concept D also applied bolt and nuts to attach the blades to the rotor that ease for maintenance. However, concept D obtains three – signs from the fields of density, strength, and design simplicity. The material used in concept D has lower density and strength compared to the DATUM. The design of blades of concept D also more complex compared to DATUM. The concept D obtains a total of two + signs, and three – sign. Lastly, concept E is a Savonius type wind turbine with curved blade design that manufactured with polycarbonate, the blades are attached to the rotor using rivets, and has a diameter of 25cm. Concept E obtains four + signs from fields of density, cost, design simplicity, and ease of maintenance. The material used in concept E has lower density and cost compared to DATUM. Besides that, concept E has applied simpler blades design compared to the DATUM. The concept E also used rivets to attach the blades to the rotor which ease for maintenance. However, concept E obtains one – sign from the field of strength. The material used in concept E has higher lower strength compared to the DATUM. The concept E obtains a total of four + signs, and one – signs. From the decision matrix above, the concept B and E both have the most number of + sign and least number of – sign which are a total of four +signs and one -signs.

Table 1
Morphological chart

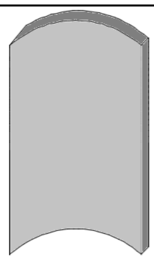
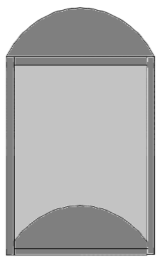
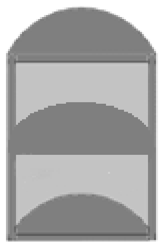
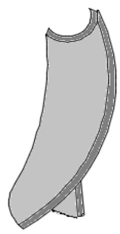
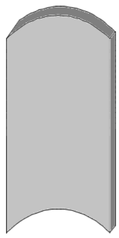
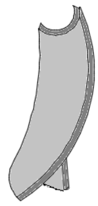
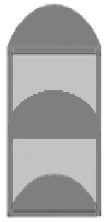
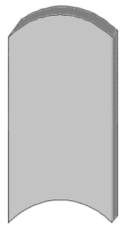
Parameter	Possible Solution			
Design of blade	 Curved	 Half-cylinder	 Half-cylinder with middle support	 Helical
Material	Polypropylene	Polycarbonate	CFRP	GFRP
○ Density (g/cm^3)	○ 0.9	○ 1.20	○ 1.50	○ 1.80
○ Tensile strength (MPa)	○ 30	○ 55-75	○ 600-3690	○ 480-1600
Method of blades attach to rotor	Permanent welded	Slide-in	Bolts and nuts	Rivets
Diameter of wind turbine	20cm	25cm	30cm	35cm

Table 2
Morphological chart

	Concepts				
Criteria	A	B	C	D	E
					
Material	CFRP	Polypropylene	CFRP	GFRP	Polycarbonate
○ Density (g/ cm^3)	○ 1.50	○ 0.90	○ 1.50	○ 1.80	○ 1.20
○ Tensile strength (MPa)	○ 600-3690	○ 30	○ 600-3690	○ 480-1600	○ 55-75
Method of blades attach to rotor	Permanent welded	Slide-in	Permanent welded	Bolts and nuts	Rivets
Diameter of wind turbine	20cm	25cm	30cm	35cm	25cm
Density	D	+	0	-	+
Cost	A	+	0	+	+
Strength	T	-	0	-	-
Design simplicity	U	+	-	-	+
Ease of maintenance	M	+	0	+	+
Sum of (+)		4	0	2	4
Sum of (-)		1	1	3	1
Sum of 0's		0	4	0	0

The parametric design of Savonius type wind turbine is used for analysis using Inspire 2017 in order to know the stress distribution over the blades when wind force is applied on the blades. The rotor is supported in a fixed position and the design is tested by applying wind energy to the blade. The wind force only applied to one of the blades since all the blades are the same in design. The wind forces are applied at different positions, which are the edge of the blade, and uniform distribution throughout the surface of the blade as shown in Figure 5 and Figure 6 respectively to investigate the effects of different wind penetration positions to the blade. The force and pressure is manipulated in order to investigate the stress distribution of the blade as the force or pressure increase. The force or pressure are manipulated in the range of wind speed of 0 – 24 m/s [16]. The maximum displacement, maximum tension/compression stress, maximum shear stress, maximum von Mises stress, maximum major principal stress, and the factor of safety for corresponding force or pressure applied are shown in Table 3 and Table 4.

From the results obtained, the blade that tested with force at the edge of blade has lower maximum displacement, maximum tension/compression stress, maximum shear stress, maximum von Mises stress, and maximum major principal stress compared to the blade that tested with uniform distributed pressure over the surface of blade at corresponding wind speed. The factor of safety is higher for the blade tested with force at the edge of blade compared to the blade tested with uniform distributed pressure over the surface of the blade at corresponding wind speed. This means that the blade tested with force at the edge of the blade is safer since the stress experienced is lower. The factor of safeties of blade tested at wind speeds in the range of 0-24 m/s is higher than 1 which means the blade is safe at under the range of wind speeds [17].

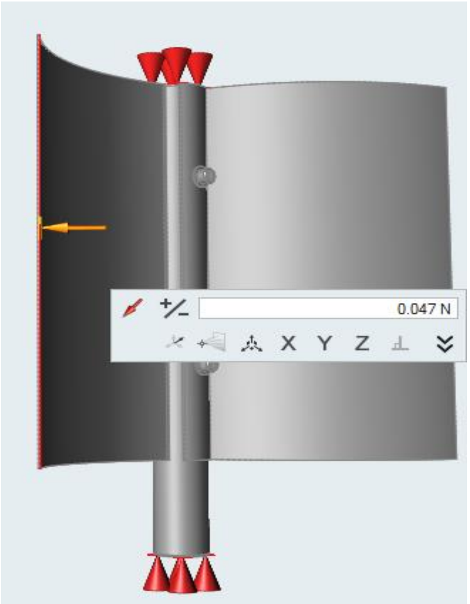


Fig. 5. Wind force to edge of blade

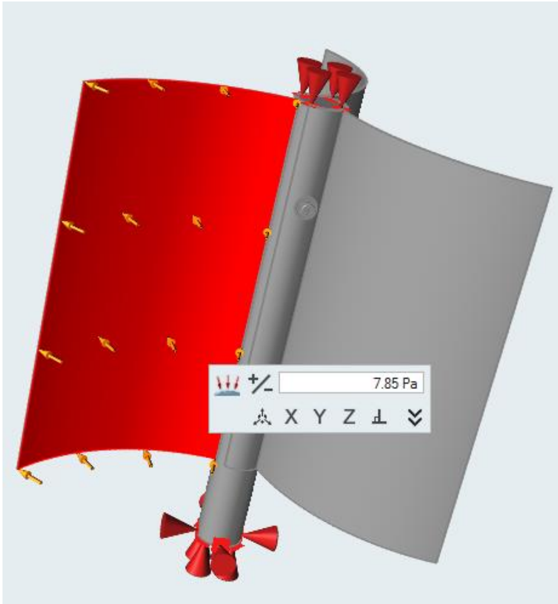


Fig. 6. Uniform distributed pressure from wind

Table 3
Displacement and Stress Analysis (Force at Edge)

Wind Speed (m/s)	Force (N)	Max Displacement (m)	Max Tension/ Compression Stress (MPa)	Max Shear Stress (MPa)	Max Von Mises Stress (MPa)	Max Major Principal Stress (MPa)	Factor of Safety
0	0	0	0	0	0	0	-
2	0.0147	3.634×10^{-4}	0.058	0.034	0.068	0.066	3155
4	0.0588	1.454×10^{-3}	0.233	0.136	0.273	0.265	788.9
6	0.1323	3.271×10^{-3}	0.525	0.307	0.613	0.595	350.6
8	0.2352	5.815×10^{-3}	0.934	0.546	1.090	1.058	197.2
10	0.3675	9.086×10^{-3}	1.459	0.853	1.703	1.654	126.2
12	0.5292	1.308×10^{-2}	2.101	1.228	2.453	2.381	87.7
14	0.7203	1.781×10^{-2}	2.859	1.671	3.390	3.241	64.4
16	0.9408	2.326×10^{-2}	3.735	2.183	4.361	4.233	49.3
18	1.1907	2.944×10^{-2}	4.727	2.763	5.519	5.358	39.0
20	1.4700	3.634×10^{-2}	5.835	3.411	6.814	6.614	31.6
22	1.7787	4.397×10^{-2}	7.061	4.127	8.245	8.003	26.1
24	2.1168	5.233×10^{-2}	8.403	4.911	9.812	9.525	21.9

Table 4
Displacement and Stress Analysis (Pressure on Blade Surface)

Wind Speed (m/s)	Pressure (Pa)	Max Displacement (m)	Max Tension/ Compression Stress (MPa)	Max Shear Stress (MPa)	Max Von Mises Stress (MPa)	Max Major Principal Stress (MPa)	Factor of Safety
0	0	0	0	0	0	0	-
2	2.45	5.111×10^{-4}	0.102	0.058	0.114	0.114	1887
4	9.80	1.456×10^{-3}	0.403	0.230	0.414	0.451	519.7
6	22.05	3.277×10^{-3}	0.906	0.517	0.931	1.015	231.0
8	39.20	5.825×10^{-3}	1.610	0.918	1.655	1.805	129.9
10	61.25	9.102×10^{-3}	2.515	1.435	2.586	2.820	83.2
12	88.20	1.840×10^{-2}	3.657	2.086	4.101	4.089	52.4
14	120.05	2.504×10^{-2}	5.005	2.857	5.570	5.588	38.5
16	156.80	3.271×10^{-2}	6.501	3.709	7.291	7.269	29.5
18	198.45	4.140×10^{-2}	8.228	4.695	9.228	9.200	23.3
20	245.00	5.111×10^{-2}	10.21	5.830	11.37	11.40	18.9
22	296.45	6.184×10^{-2}	12.36	7.054	13.75	13.80	15.6
24	352.80	7.360×10^{-2}	14.71	8.395	16.37	16.42	13.1

4. Conclusions

The first objective is to design the concepts of Savonius type VAWT with different blades design and different methods of blades attach to rotor. There are 4 possible solutions suggested for each parameter including blade designs, material used, method of blades attach to the rotor, and diameter of wind turbine. All these possible solutions are combined and 256 different types of concepts of Savonius type VAWT had been developed. The 5 concepts had been chosen from 256 concepts and the best design was selected using Pugh Method. The second objective is to analyze the displacement and stress applied to the structure by wind. The stress distribution over the blades is analyzed using Inspire 2017. There are two types of force distribution used for analysis, which are along the edge of blade, and uniformly distributed throughout the surface of blade. The wind speeds used to analyze the blades are in the range of 0-24 m/s. The result from the analysis is shown using colour indication. The results shown most of the stress are higher at the area near to the rotor as the wind energy applied to the blade. The last objective is to optimize the blade design using topology optimization. The blade is optimized using Inspire 2017 through topology optimization. The result of the optimization shows that the blade design is already at optimum state which means no parts needed to be deducted from the design.

Acknowledgement
Author would like to thank Universiti Teknikal Malaysia Melaka (UTeM) and Ministry of Higher Education (MOHE) for financial support under internal grant PJP/2018/FTK(7B)/S01599.

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