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ORIGINAL ARTICLE

Wind Turbine Plate Thickness Design Optimization

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ABSTRACT –The design of the blade thickness of the Darrieus wind turbine should be optimized. This study aims to obtain the optimal thickness of the blade plate so that its weight and strength can be optimal. The design begins with preliminary calculations to find the optimal dimensions based on a wind speed of 15 m/s. The blade design was drawn in 2D using AutoCAD software, followed by 3D manufacturing, and material stress analysis was carried out with Autodesk Inventor software. The optimization of the yield stress value compared to the applied stress is 3.0. The software simulation of stress analysis results found that the most optimal thickness was 0.2 mm at variant B-3.

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Darrieus Wind Turbine
Safety Factor
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INTRODUCTION

1.1 BACKGROUND

Energy is one of the primary needs of human life. The increasing energy demand indicates rising prosperity; however, it challenges ensuring its supply [1] – [3]. According to the data released by the Ministry of Energy and Mineral Resources [4], it is stated that the demand for electrical energy in Indonesia continues to rise annually. Additionally, following the economic downturn in 1998, there was a significant surge in energy consumption in Indonesia, growing at an annual rate of 7%. Yet, this increase was not met with a sufficient energy supply [5].

In Indonesia, fossil fuels, coal, and gas remain the primary sources of energy generation [6], [7]. However, because the number of needs continues to increase and is not matched by its availability in nature, conventional fuels that exist in nature are increasingly depleting in number [8]. This has led the country to seek new and renewable alternative energy sources like biomass, hydropower, wind, micro-hydro, and solar energy to replace conventional fuels [9].

Indonesia has the potential to utilize wind energy, which is quite adequate [7], [10]. Data released by the website of the Cabinet secretary shows that the General National Energy Plan (RUEN) lists the figure of 60,647.0 MW for wind speeds of 4 meters per second or more (Attachment to Presidential Regulation Number 22 of 2017) [11].

A wind turbine is a device that can convert the wind's kinetic energy into electrical energy [12]. Various inventions of wind turbines as alternative energy have been found for a long time with multiple forms of design, and each type has its advantages [13]. Because the characteristics of the wind in Indonesia have a low average speed [14], [15], the type of wind turbine that suits this problem is a vertical axis wind turbine because it has a sizeable initial torque at low wind speeds [16]. The Darrieus type wind turbine is a vertical axis wind turbine that can take advantage of low and variable wind speeds [17], [18], can receive wind from all directions to generate electricity, and is very suitable for application in Indonesia's geographical conditions.

In this study, an analysis will be carried out on the vertical axis Darrieus wind turbine blade, capable of producing 20 Watts of electricity at a speed of 3 m/s. The study aims to find the best design optimization of the blade's thickness, which can withstand the load from the drag force due to the design wind speed of 15 m/s.
The main parts of the turbine can be seen in Figure 1 below:

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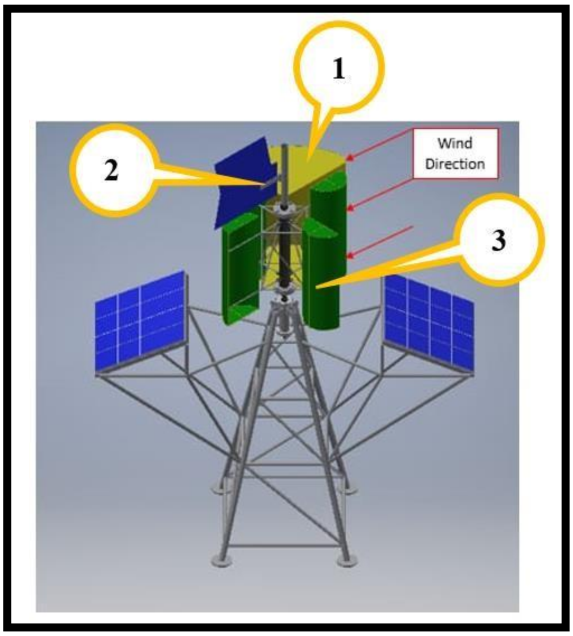


Figure 1. Main Parts of the Darrieus Turbine
: 1. Deflector, 2. Tail Guide, 3. Blade

1.2 LITERATURE STUDY

The simple problem of the bending of a long rectangular plate that is subjected to a transverse load that does not vary along the length of the plate. The deflected surface of a portion of such a plate at a considerable distance from the ends1 can be assumed cylindrical, with the axis of the cylinder parallel to the length of the plate. We can therefore restrict ourselves to the investigation of the bending of an elemental strip cut from the plate by two planes perpendicular to the length of the plate and a unit distance (say 1 in.) apart. The deflection of this strip is given by a differential equation which is similar to the deflection equation of a bent beam. To obtain the equation for the deflection, we consider a plate of uniform thickness, equal to h, and take the xy plane as the middle plane of the plate before loading, i.e., as the plane midway between the faces of the plate. Let the y axis coincide with one of the longitudinal edges of the plate and let the positive direction of the z axis be downward, as shown in Fig. 1. [19}

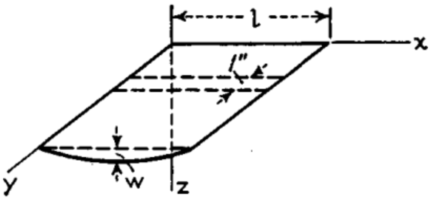


Figure 2.

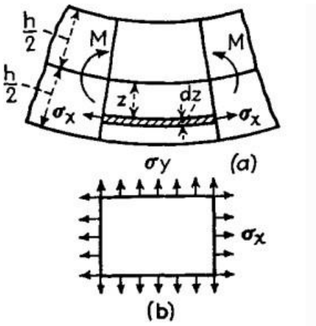


Figure 2.

The curvature of the deflection curve can be taken equal to —d2w/dx2, where w, the deflection of the bar in the z direction, is assumed to be small compared with the length of the bar I. The unit elongation ex of a fiber at a distance z from the middle surface (Fig. 2) is then - z d2w/dx2 . Making use of Hooke's law, the unit elongations ex and ey in terms of the normal stresses (Tx and ay acting on the element shown shaded in Fig. 2a are

$$\in_x = \frac{\sigma_x}{E} - \frac{v\sigma_y}{E}$$

$$\in_y = \frac{\sigma_y}{E} - \frac{v\sigma_x}{E} = 0 \qquad (1)$$

Where E is the modulus of elasticity of the material and v is Poisson's ratio. The lateral strain in the y direction must be zero in order to maintain continuity in the plate during bending, from which it follows by the second of the equations (1) that ay = vax. Substituting this value in the first of the equations (1) we obtain

$$\in_x = \frac{(1-v^2)\sigma_x}{E}$$

$$\sigma_x = \frac{E\epsilon_x}{(1-v^2)} = -\frac{Ez}{(1-v^2)} \cdot \frac{d^2w}{dx^2} \qquad (2)$$

Having the expression for bending stress ax, we obtain by integration the bending moment in the elemental strip:

$$M = \int_{-h/2}^{h/2} \sigma_x z dz = \int_{-h/2}^{h/2} \frac{Ez^2}{(1-v^2)} \frac{d^2w}{dx^2} dz = -\frac{Eh^3}{12(1-v^2)} \frac{d^2w}{dx^2}$$

Introducing the notation

$$\frac{Eh^3}{12(1-v^2)} = D \qquad (3)$$

we represent the equation for the deflection curve of the elemental strip in the following form:

$$D\frac{d^2w}{dx^2} = -M \tag{4}$$

In which the quantity D, taking the place of the quantity EI in the case of beams, is called the flexural rigidity of the plate. The maximum stress occurs at the middle of the strip, where the bending moment is a maximum. From the differential equation (4) the maximum bending moment is

$$M_{max} = -D\left(\frac{d^2w}{dx^2}\right)_{x=l/2} \tag{5}$$

The effective Von Mises stress (σ) is defined as a uniaxial tensile stress that can produce a stress with the same distortion energy as the combined working stress, as mentioned in Arora [20] where:

$$\sigma' = \sqrt{\sigma_1{}^2 + \sigma_2{}^2 + \sigma_3{}^2 - \sigma_1\sigma_2 - \sigma_2\sigma_3 - \sigma_1\sigma_3} \tag{6}$$

$$\sigma' = \sqrt{(\sigma_x - \sigma_y)^2 + (\sigma_y - \sigma_z)^2 + (\sigma_z - \sigma_x)^2 + 6(\tau_{xy}{}^2 + \tau_{yz}{}^2 + \tau_{zx}{}^2)} \tag{7}$$

$$\sigma = \frac{F}{A} \tag{8}$$

The optimization design of all variants will be taken by comparing the yield strength (σ_y) to the effective stress of Von Mises (σ') which is called the factor of safety (*SF*), where the optimization of $SF = \frac{\sigma_y}{\sigma'} \geq 3$

The thickness of the blade plate [21] in this study consisted of 5 variants. Starting from the B-1 blade with a thickness of 0.1 mm, the B-2 blade with a thickness of 0.15 mm, the B-3 blade with a thickness of 0.2 mm, the B-4 blade with a thickness of 0.25 mm, and the B-5 blade with a thickness of 0.3 mm. The material used in the stress analysis on the Darrieus wind turbine is JIS G3101 Grade SS400. The drag force is calculated according to [22]:

$$Fd = \frac{1}{2}.\rho.Cd.A.V^2 \tag{9}$$

As an input of stress simulation, the drag force is converted into pressure based on the cross-sectional area of the blade with the equation :

$$\text{P} = \frac{Fd}{A} \tag{10}$$

RESEARCH METHODOLOGY

This research was conducted at the Design Laboratory, Mechanical Engineering, Universitas Negeri Jakarta. The flow chart can be seen in the Figure 2 below:

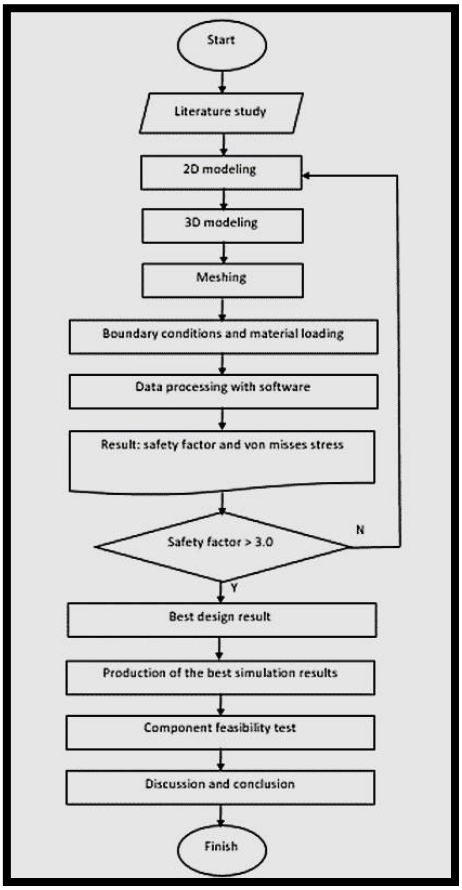


Figure 2. Flowchart of Optimization

From the literature study, the 2D and 3D blade geometry is modeled using the AutoCAD and Inventor software. The next stage is meshing to divide geometry into small parts in lines connected to nodes spread throughout the object's geometry. After meshing, the stress analysis feature is used to determine boundary conditions and material loading in the Inventor software. The next stage is data processing with software simulation. This simulation is carried out in the form of stress analysis. Then, the simulation results are von Mises stresses and safety factor values, which are used to determine the optimum design of blade thickness. The optimum design point if the safety factor is close to SF = 3.

2.1 DATA OF WIND TURBINE

The 2D wind turbine design can be seen in Figure 2 below :

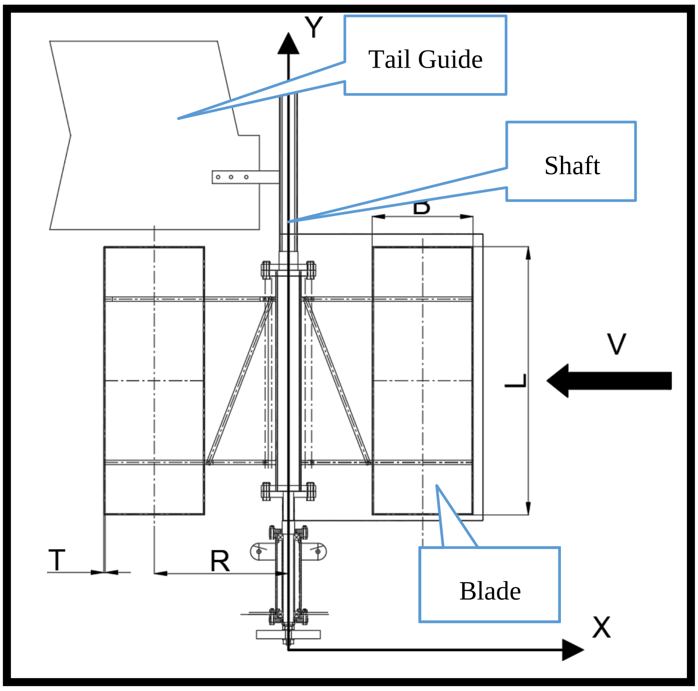


Figure 3. 2D Darrieus Wind Turbine Design

Figure 1 above represents a 2D model of a Darrieus wind turbine with horizontal axis X and vertical axis Y and several components, including the blades, tail guide, and shaft. The wind speed direction from the right side of the turbine at a design speed of 15 m/s. Parameters and data can be seen in Table 1 below:

Table 1. Parameters and Data of Darrieus Wind Turbine.

Design Parameter	Design Dimension	Description
L	640 mm	Blade Height
B	240 mm	Blade Width
T	0.1-0.3 mm	Variants Thickness of Blade
V	15 m/s	Design Wind Speed
Fd	47,7 N	Drag Force
P	310,5 Pa	Blade Projected Area Pressure

In Table 1, there are design parameters for the Darrieus wind turbine, providing information about the blade length (L) of 640 mm, blade width (B) of 240 mm, and blade thickness variation (T) ranging from 0.1 to 0.3 mm. The wind speed (v) received by the blade is 15 m/s. The drag force (Fd) received by the blade can be calculated using equation

(9), resulting in a value of 47.7 N. Meanwhile, the pressure (P) on the blade is derived from equation (10), yielding a value of 310.5 Pa.

2.2 BLADE THICKNESS VARIATION

There are five variants of blades with different thicknesses to get the best or optimum design, as shown in Table 2 below.

Table 2. Variation of Blade Thickness

Variant	Thickness (mm)
B-1	0,1
B-2	0,15
B-3	0.2
B-4	0,25
B-5	0,3

2.3 BOUNDARY CONDITIONS

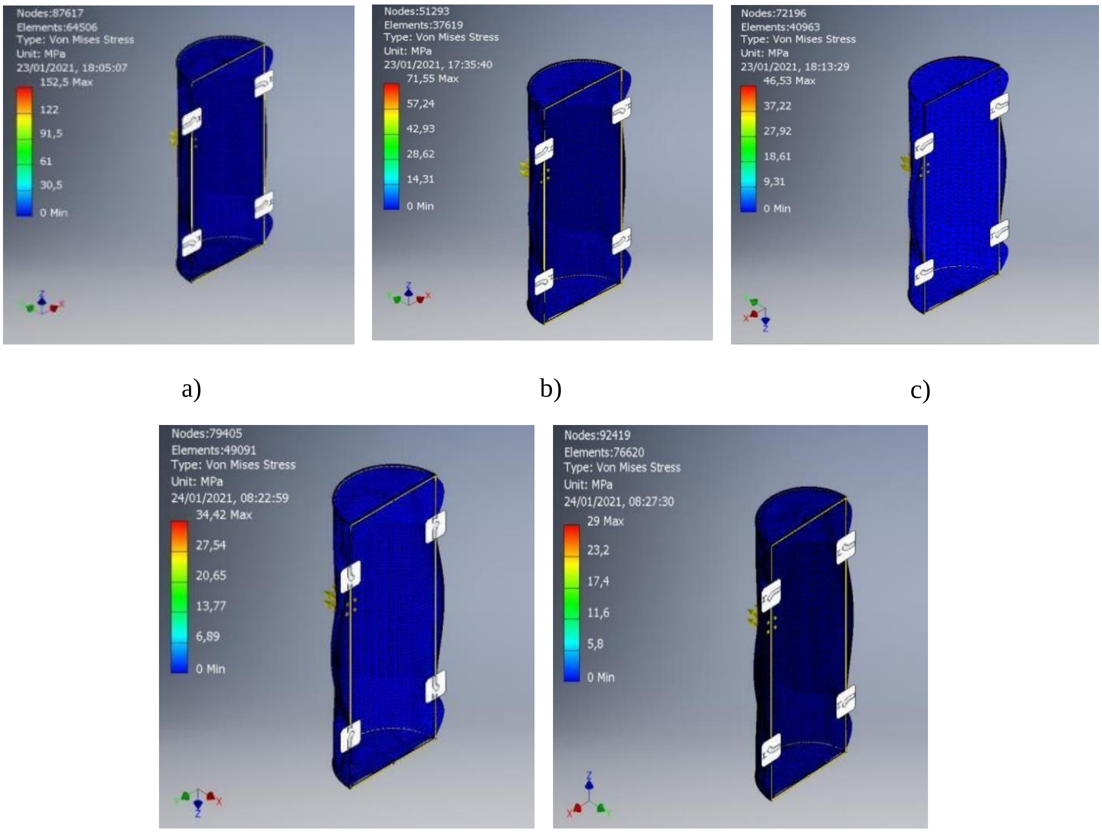
To get the results of the simulation, it is necessary to input the boundary conditions. Those data can be seen in Table 3 below:

Table 3. Boundary Conditions for Simulation

No	Items	Blade Frame	Blade Blanket
1	Material Type	JIS 3101 SS-400	Zinc
2	Material Density	7.86 g/cm^3	7 g/cm^3
3	Yield Strength	207 MPa	150 Mpa
4	Ultimate Tensile Strength	345 MPa	259 Mpa
5	Young Modulus	210 Gpa	85 Gpa
6	Poisson's Ratio	0.3	0.25
7	Shear Modulus	80.7692	43 Gpa
8	Design Wind Speed	15 m/s	15 m/s
9	Drag Force due to wind speed	47.7 N	47.7 N

RESULTS AND DISCUSSION

In the simulation phase of the analysis for all blade variations, it begins with inputting the boundary conditions listed in tables 1 and 3. Following that, meshing is performed using triangular-shaped elements with a mesh size of 0.2. Critical points requiring refinement of the mesh size are located at the middle section of the blade, where it experiences a load of 310.5 Pa. The results of the Blade turbine Stress Analysis can be seen in the following Figure 4

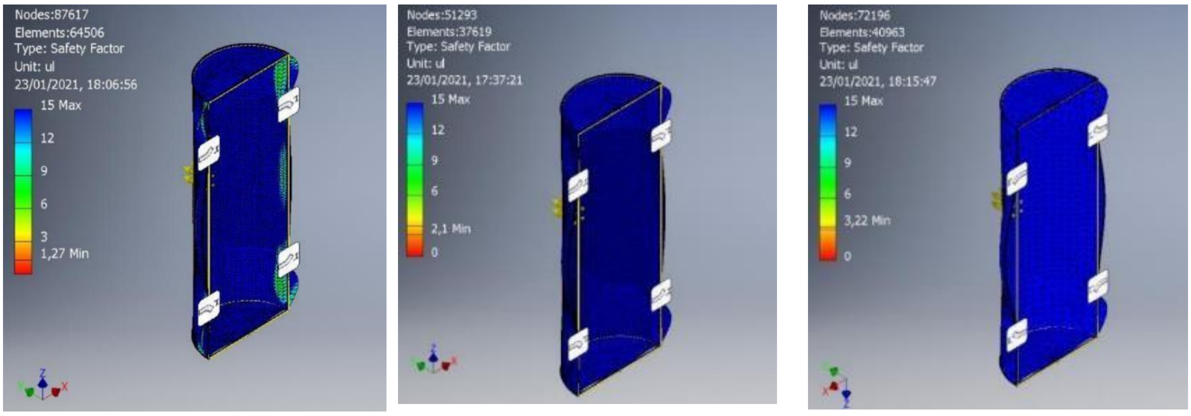


a) b) c)

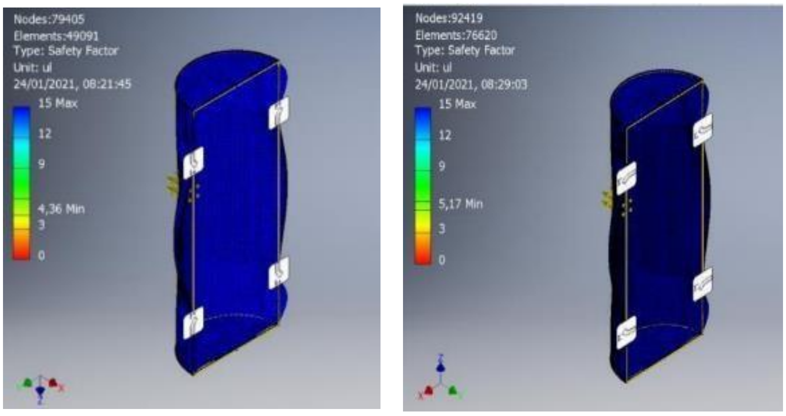
d) e)

Figure 4. Effective Von Mises Stress for Variants : a) B-1, b) B-2, c) B-3, d) B-4, e) B-5

Figure 4 show that the maximum stress that occurs in the middle of the turbine blade for variant B-1 is 152.5 MPa, B-2 is 71.55 MPa, B-3 is 46,53 Mpa, B-4 is 34,42 Mpa, and B-5 is 29 Mpa This data shown that if the thickness increase, the stress acting will be reduced. The corelation between Von Mises stress is inversely proportional to the thickness of the blade. This study proves that the maximum Von Mises stress can be reduced by increasing the thickness of the Darrieus wind turbine blade.



a) b) c)



d) e)

Figure 5. Factor of Safety for Variants : a) B-1, b) B-2, c) B-3, d) B-4, e) B-5

Figure 5 show the result of the safety factor for variant B-1 is 1,27, B-2 is 2,1, B-3 is 3,22, B-4 is 4,36, and B-5 is 5,17. The simulation results indicate that as the blade thickness increases, the safety factor also increases. The corelation between blade thickness and safety factor is linear, while the corelation safety factor and maximum Von Mises stress is inversely proportional as per the equation $SF = \frac{\sigma_y}{\sigma'} \geq 3$ In variant B-3, the safety factor is 3.22; this value is very close to SF = 3. The results and discussion above show that the effect of blade thickness and variant B-3 is the best result because the Safety Factor is close to 3 and the best thickness is 0.2 mm.

CONCLUSION

From the results and discussion above can be concluded:

1. The Von Misses stress is reduced with the increase in thickness of the blade plate. For variant B-1 with 0.1 mm thickness, the stress is 152.5 Mpa; for variant B-2 with 0,15 mm, it is 71.55 Mpa; for variant B-3 with 0.2 mm, it is 46.53 Mpa; for variant, B-4 with 0.25 mm is 34.42 Mpa and for variant B-5 with 0.3 mm is 29 Mpa.
2. The safety factor increases with the thickness of the blade increases. For variant B-1 of a thickness of 0.1 mm, the safety factor is 1.27; for variant B-2 of a thickness of 0.15 mm, the safety factor is 2.1; for variant B-3 of a thickness of 0.2 mm, the safety factor is 3.22; for variant B-4 of the thickness 0.25 mm, the safety factor is 4.36 and for variant B-5 of the thickness 0.3 mm, the safety factor is 5.17
3. Variant B-3, with a thickness of 0.2 mm, is the most optimum because the safety factor is 3.22. This value is very close to 3.

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