INTEGRATION OF OPEN TYPE WIND TUNNEL STRUCTURAL DESIGN AND PERFORMANCE ANALYSIS OF BAYU MICRO POWER PLANT TRANSMISSION SYSTEM

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Abstract

In the midst of global efforts to reduce dependence on fossil energy, the development of renewable energy technology in Indonesia is a strategic priority, especially in achieving the national energy mix target of 23% by 2025. This research integrates two fundamental aspects in the development of laboratory-scale wind energy research infrastructure: structural *design* of *the open type* wind tunnel *body* and performance analysis of mechanical transmission systems in micro-wind power plants operated in them. The first part of the research focuses on the validation of the structural design of wind tunnels using the *finite element analysis* (FEA) method with carbon steel and acrylic materials. The analysis carried out included the evaluation of *von Mises* voltage, strain, *displacement*, and safety factors in *the* components of the contraction chamber, *turbine box*, *test section*, and *diffuser*. The simulation results showed an exceptionally high structural integrity, with a *Safety Factor* value of 677,006 on the *diffuser components*, indicating a very safe design but leaving room for material optimization. The second part of the study evaluated the effectiveness of the transmission system using *a 1:1 ratio pulley timing and* a V-belt on the Savonius turbine (3 and 4 spoons). Empirical tests show that a 4-blade turbine produces superior performance with a rotational speed of 137.3 RPM and an electrical power of 16.8 Watts, compared to a 3-blade turbine that produces only 3.6 Watts. However, an inefficiency in the transmission system was found due to a mismatch in the belt dimensions that caused *mechanical losses*. The integration of these two studies provides a comprehensive blueprint for the development of robust and functional aerodynamic test tools for renewable energy applications in academic environments.

Keywords: Wind Tunnel, *Finite Element Analysis* (FEA), Savonius Turbine, Transmission System, Renewable Energy, *Safety Factor*.

Background

The development of modern human civilization is inseparable from the ever-increasing need for energy. However, global reality shows that the world's fossil energy reserves are decreasing significantly every year. The International Energy Agency (IEA) predicts global energy demand will increase by 45% by 2030, with an average growth rate of 1.6% per year[1]. Excessive reliance on fossil energy, which currently still supplies about 80% of the world's energy needs, demands an immediate transition to new and renewable energy (NRE) sources.

In Indonesia, this commitment to energy transition is contained in Government Regulation Number 79 of 2014 concerning National Energy Policy. The government targets the contribution of renewable energy in the national energy mix to reach at least 23% by 2025 and increase to 31% by 2050[2]. One of the largest potentials that the archipelago has is wind energy, with a theoretical potential of 60.6 GW. The use of wind energy, especially through Wind Power Plants (PLTB), offers sustainable environmentally friendly solutions. However, the development of efficient wind turbine technology requires a deep understanding of the behavior of airflow and its interaction with solid objects, a discipline known as aerodynamics.

To support research and development in the field of aerodynamics and wind energy conversion, the existence of adequate testing facilities is absolutely necessary. A *wind tunnel* is a standard device used to simulate the flow of air around a test object under controlled conditions. This tool allows researchers to measure aerodynamic forces such as *lift*, downforce, and drag and visualize complex airflow patterns.[3] In the context of laboratory-scale education and research, *open circuit* wind tunnels are often the preferred choice because of their simpler design and lower construction costs than closed-circuit types.

Although the working principle is simple, wind tunnel design faces multidimensional technical challenges. First, from a structural perspective, the wind tunnel body must be designed with precision to ensure stable airflow and minimal turbulence. In addition, the structure must have sufficient mechanical strength to withstand static loads (self-weight) and dynamic loads (airflow pressure and operational vibration). Structural failure not only risks damaging equipment but also jeopardizes operator safety. Therefore, the application of modern analysis methods such as *Finite Element Analysis* (FEA) is crucial to predict stress distribution and deformation before the fabrication process is carried out[4].

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[1] Rifai, T., Gunadi, G. G. R., & Ridwan, E. (2021). Rancang Bangun Pembangkit Listrik Tenaga Bayu (Angin) Mikro Turbin Savonius pada Jalan Tol Jatiasih. *Jurnal Mekanik Terapan*, 2(2), 82–88. https://doi.org/10.32722/jmt.v2i2.4423

[2] Maulana, E., Djatmiko, E., Mahandika, D., & Putra, R. C. (2021). Perancangan Pembangkit Listrik Tenaga Angin dengan Turbin Angin Savonius Tipe-U untuk Kapasitas 100 W. *Jurnal Asiimetrik: Jurnal Ilmiah Rekayasa & Inovasi*, *3*, 183–190. https://doi.org/10.35814/asiimetrik.v3i2.2164

[3] Aji Saputra, R., Indra Partha, C. G., & Sukerayasa, I. W. (2021). Rancang Bangun Sistem Pemanen Energi Angin Exhaust Fan Turbin Angin Sumbu Horizontal Dengan Pengarah Angin (Wind Tunnel). *Jurnal SPEKTRUM*, *8*(2), 229. https://doi.org/10.24843/spektrum.2021.v08.i02.p26

[4] Pradana, M. R. B., Anam, C., Yuniwati, I., Lazuardi, M., & Sari, E. N. (n.d.). *ANALISIS KEKUATAN BEARING PADA MESIN GRANULATOR TERHADAP PEMBEBANAN STATIS MENGGUNAKAN METODE FINITE ELEMENT ANALYSIS (FEA)*. 24(2), 45–49.

Second, in terms of functionality as an energy test tool, the effectiveness of wind tunnels is measured by their ability to facilitate wind turbine performance testing. One of the critical components in a wind power generation system is the transmission system, which functions to transfer mechanical power from the turbine shaft to the generator. The efficiency of the transmission system greatly determines the amount of electrical power that can be extracted. Previous research has indicated that the use of *pulleys* and *V-belts* offers an economical and easy-to-maintain transmission solution, but is susceptible to slip power loss if not designed with the right belt ratio and voltage[5].

Based on the background that has been described, this study formulates several main problems that will be solved systematically:

1. Structural Design Aspect: How to design the shape and dimensions *of an* open-type wind tunnel body that is effective in producing stable airflow, as well as determining the right material specifications to ensure the strength and resistance of the structure to operational loads?
2. Aspect of Force Analysis: How is the distribution of maximum voltage, strain, and *displacement* in the main components of the wind tunnel (*contraction chamber, turbine box, test section, diffuser*) when analyzed using the finite element method (FEA), and how much of the *Safety Factor* is produced?
3. Transmission System Aspects: How to design an optimal transmission system using *timing pulleys* and *V-belts* for the Savonius turbine-type micro-wind power plant in the wind tunnel?
4. Energy Conversion Performance Aspects: How does the variation in the number of blades of a Savonius turbine (3 tablespoons vs 4 tablespoons) affect the characteristics of rotation, torque, mechanical power, and electrical power generated through the designed transmission system?

Research Objectives

This research aims to achieve the following objectives:

1. What is the design of the transmission system for wind tunnel micro power plants?
2. How is the analysis of the results of the transmission system design for wind tunnel micro power plants?

[5] Rey, P. D., Aziz, A., Hermawan, D., Muhammad,), Nurkhozin, F., Teknik, J., Fakultas, M., Dan, S., Universitas, T., As-Syafi'iyah, I., Besar, B., Konversi, T., & Bppt, E. (2020). Webinar Nasional Cendekiawan Ke 6 Tahun 2020. In *KOCENIN Serial Konferensi* (Issue 1).

3. How to design the shape and dimensions of an open type wind tunnel body that is effective in producing stable airflow?
4. How to determine the material to ensure the strength and resistance of the wind tunnel body to pressure and wind flow?

THEORETICAL STUDIES

Basic Concept of Wind *Tunnel*

Wind tunnels are aerodynamic research instruments designed to simulate the interaction between airflow and solid objects. Its working principle is based on the relativity of motion; Instead of moving objects through stationary air (such as airplanes in the sky), wind tunnels flow air through stationary objects. It was first operated by Francis Herbert Wenham in 1871 for the Aeronautical Society of Great Britain [6].

Classification of Wind Tunnels

Based on their air circulation, wind tunnels are categorized into two main types[7]:

1. Open Circuit Wind Tunnel: In this type, air is taken directly from the environment (atmosphere), flowed through the test section, and then discharged back into the atmosphere.
    - *Pros:* The construction design is simpler and the fabrication cost is relatively cheap.
    - *Disadvantages:* The quality of airflow is greatly affected by the conditions of the outside environment (temperature, humidity, dust), and requires more energy to move the mass of stationary air continuously.
    - *Characteristics:* The test duct is open at both ends, suitable for testing small-scale models such as automotive aerodynamics or architecture.[1]
2. Closed Circuit *Wind Tunnel*: Air is circulated continuously in a closed channel. This type allows for more precise control of variables (temperature, pressure), higher energy efficiency, and lower noise levels, but with much higher complexity and construction costs.

Main Components of Wind Tunnel

The effectiveness of a wind tunnel depends on its constituent components[8]:

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[6] Pendidikan, J., & Arab, B. (2022). *Vol. 1 No. 2 Desember 2022. 1*(2), 12–25.
Pradana, M. R. B., Anam, C., Yuniwati, I., Lazuardi, M., & Sari, E. N. (n.d.).
[7] Hidayat, M. F., & Xaverius, F. (2022). Rancang Bangun Terowongan Angin Kecepatan Rendah Tipe Terbuka Sederhana dengan Smoke Generator Sebagai Visualisasi Aliran Udara Untuk Alat Pratikum. *Jurnal Kajian Teknik Mesin*, *7*(2), 63–72. http://journal.uta45jakarta.ac.id/index.php/jktm/article/view/6459%0Ahttp://journal.uta45jakarta.ac.id/index.php/jktm/article/download/6459/2282
[8] Aditya, V., Alchalil, A., Asnawi, A., & Rahman, A. (2023). Analisa Indikator Kinerja Terowongan Angin Rangkaian Terbuka (Open Circuit Wind Tunnel) Tipe Subsonic. *Malikussaleh Journal of Mechanical Science and Technology*, *7*(2), 120.

- Settling *Chamber*: Located at the *inlet*, it serves to straighten the incoming airflow and reduce turbulence. These components are often equipped with *honeycombs* (honeycomb structures) and *screens*.[1]
- Honeycomb: A structure with hexagonal, square, or cylindrical cells that function to control airflow. As the turbulent flow passes through the narrow gaps of *the honeycomb*, the lateral velocity component is dampened so that the flow becomes more laminar.
- Contraction *Cone*: A part of the duct that narrows gradually. Based on the law of fluid continuity ($A_1V_1 = A_2V_2$), the reduction of the cross-sectional area (A) will increase the speed of airflow (V). Its main function is to accelerate the airflow before it enters the test chamber and improve the uniformity of the speed profile.
- Test Section: The main working area where the test object is placed. In this section, the airflow is expected to have a uniform speed and minimum turbulence. Test room walls are often made of transparent materials (such as acrylic) to allow for visual observation and the use of flow visualization techniques (e.g. using smoke).
- Diffuser: A channel that gradually widens after the test chamber. Its function is to decrease the speed of airflow (*decelerate*) before it is discharged into the environment, which aims to recover static pressure and reduce energy loss, thereby increasing fan efficiency.
- Drive Unit (*Blower Fan*): A source of energy that generates airflow. It is usually an axial or centrifugal fan that is placed at the end (suction type) or beginning (blowing type) of the tunnel.

Savonius Micro Power Plant and Turbine

Wind energy is a form of kinetic energy produced by the movement of air masses due to differences in atmospheric pressure. Wind Power Plants (PLTB) convert this kinetic energy into rotational mechanical energy through turbines, and subsequently into electrical energy through generators[9].

Savonius turbines are a type of vertical *axis wind turbine* (VAWT) that works on the principle of drag. Unlike elevator-type turbines that require complex airfoil designs, the Savonius has a simple construction that resembles the letter 'S' when viewed from above.

- *Advantages:* Able to rotate at low *cut-in speed*, independent of wind direction (*omnidirectional*), and has a high starting torque.

https://doi.org/10.29103/mjmst.v7i2.13658

[9] Daingah, L. M., Tangkuman, S., & Punuhsingon, C. (2022). Perancangan Gearbox Turbin Angin Savonius Tipe-L Untuk Pembangkit Listrik Pada Rumah Tinggal. *Jurnal Poros Teknik Mesin Unsrat*, *11*(1), 67.

- *Application:* It is suitable for micro scale and environments with turbulent or directional wind flows.

Transmission System

A transmission system is a mechanism that transfers power and rotation from the drive source (turbine) to the load (generator). Its main function is to adjust the rotational speed and torque to match the characteristics of the generator.

Pulleys and V-Belts

Belt drive *systems* use *pulleys* and flexible belts to transmit power between shafts separated by a certain distance.

- V-Belt: A belt with a trapezoidal cross-section made of rubber and reinforcing thread. The 'V' shape provides better grip on *the pulley* groove due to *the wedging* effect, thus minimizing slip compared to flat belts.
- Advantages: Smooth and quiet operation, able to dampen shock/vibration, low cost, and easy maintenance (no lubrication required).
- Disadvantages: There is slip (friction) that causes the spin ratio to be not 100% precise, and the efficiency decreases as the belt wears out.

Important parameters in belt transmission planning include:

1. Speed Ratio: The relationship between the diameter of the driving pulley (dpA) and the driven one (dpB) with its rotational speed (n1,n2).
$$dpB = \frac{n1}{n2} \times dpA$$
2. Belt Length (L): Determined by the distance between the shafts (C) and the diameter of the two pulleys. The formula of the approach is:
$$L = 2.C + \left[(dpB + dpA)\frac{\pi}{2}\right] + [\left(\frac{(dpB - dpA)^2}{4.C}\right)$$
3. Belt Linear Velocity (V): The tangential velocity on the surface of the pulley.
$$V = \frac{\pi.dp1.n1}{60.1000}$$

Load Theory and Structural Analysis (FEA)

The design of the engineering structure must guarantee that the components are able to withstand the workload without experiencing failure[10].

Concept of Tension and Strain

- Stress: The internal force per unit area that works to resist deformation. $(\sigma) = \frac{F}{\mathrm{A}}$

[10] Suryady, S., & Sapto, A. D. (2024). *Analisis Pembebanan Statis terhadap Rangka Mesin Alat Pengaduk untuk Adonan Donat menggunakan Sofware FEA Jurnal Teknik Mesin : Vol . 13 , No . 1 , Februari 2024 ISSN 2549-2888. 13*(1), 22–29.

Where F is the force (Newton) and A is the cross-sectional area (m^2). Stresses are differentiated into normal stress (perpendicular to the surface) and shear stress (parallel to the surface).

Strain (Strain, \varepsilon): The size of the deformation of a material relative to its initial dimensions Strain is a material response to a working stress.

$$\varepsilon = \frac{\Delta l}{l}$$

Finite Element Analysis (FEA)

FEA is a computer-based numerical method for simulating physical phenomena. In structural analysis, FEA breaks down complex geometries into small elements (*mesh*) and calculates the response (stress, deformation) at each node point.

- Von Mises Stress: Failure criteria for ductile materials such as steel. This theory states that the material will yield if the distortion energy per unit volume exceeds the limit of the distortion energy when the tensile test reaches the yield point. This is the key parameter in the simulation to determine if the structure is safe.
- Displacement: The displacement of the position of points on the material due to loading. A *large displacement* value indicates low structural rigidity.
- Safety Factor (FOS): The ratio between the yield strength of the material (Yield Strength) and the maximum voltage that occurs.

A FOS value of > 1.0 must be met for safety. The higher the FOS value, the lower the risk of failure, but it can indicate an over-design.1

Engineering Materials

The selection of materials is based on mechanical, chemical, and fabricated properties.

- Carbon Steel: Chosen for *diffuser* components and contraction chambers due to high tensile strength, high modulus of elasticity (rigidity), and ease of welding.
- Acrylic: Chosen for *test sections* and turbine boxes due to its transparent properties that allow flow visualization, light weight, and strong enough for low aerodynamic loads.

RESEARCH METHODOLOGY

Research Flow Diagram

This research was carried out in systematic stages which were divided into two main flows that were integrated with each other:

1. Structural Planning & Analysis (Kherin) Level:
   - Start -> Literature Study -> Design Design (SolidWorks) -> Material Preparation (Steel Plate, Acrylic) -> Manual Calculation & FEA Simulation (Voltage, Strain, FOS) -> Data Analysis -> Conclusions.[1]
2. Transmission Planning & Testing Stage (Aditya):
   - Start -> Literature Study -> Transmission Design -> Preparation of Tools/Materials -> Design and Build Systems -> Tool Testing (Measure RPM, Torque, Electricity) -> Data Analysis -> Conclusions.[1]

Tools and Materials

This research uses a combination of fabrication hardware, measuring instruments, and construction materials.

Main Tools List:

- Software: SolidWorks (for 3D design and FEA simulation).
- Measuring Instruments: Anemometer (wind speed), Tachometer (turbine RPM), Multimeter (Voltage & electric current), Ruler & meter (dimensions), Scale (turbine mass).
- Fabrication Tools: Hand grinding (cut/smooth), Welding machine (steel jointing), Drilling machine (bolt holes), Wrench & ring (assembly), Sanding & putty (finishing).

Main Ingredient List:

1. Wind Tunnel Structure:
   - Carbon Steel Plate: 2 mm and 0.5 mm thick (for *Diffuser, Contraction*).
   - Acrylic: Thickness (assuming 2-5mm customized function) for *Box Turbine & Test Section*.
   - Elbow Iron: For the support frame.
   - Bolts & Nuts: 5 mm hole diameter for *flange connection*.[1]
2. Transmission & Generator Systems:
   - Savonius turbines: 3-tablespoon and 4-tablespoon variants.
   - *Timing Pulley*: 2 pieces (1:1 ratio).
   - *V-Belt*: Circumferential length 528 mm.
   - Shaft: Diameter 5/8 inch (As).
   - *Bearing Pillow Block*: 2 pieces.
   - DC Generator.

Design Design and Dimensions

The wind *tunnel body* design is made using SolidWorks with precision dimensional specifications to guarantee simulation and fabrication accuracy.

1. Contraction Cone:

It is a narrow 3D trapezoidal shape.

- Inlet Dimensions (Side a): 400 mm x 400 mm.
- Outlet Dimensions (Side b): 275 mm x 275 mm.
- Length/Height (t): 600 mm.
- Feature: 8 bolt holes 5 mm diameter on the *flange*.

2. Turbine Box:

A special chamber for placing the Savonius turbine, made of acrylic.

- Length: 420 mm.
- Width: 310 mm.
- Height: 255 mm.
- Feature: Transparent for visualization.

3. Test Section:

Straight channels where airflow is stable.

- Length: 800 mm.
- Cross-section: 240 mm x 240 mm (Note: there is a slight difference in connection dimensions with *a 275mm outlet contraction vs* 240mm test section which may be bridged by *a special adapter* or *flange* in the visual design).
- Height: 185 mm (internal or external dimensions vary in text, table reference is used).

4. Broadcast:

Dilating ducts for pressure recovery.

- Inlet Dimensions (Side a): 250 mm x 350 mm.
- Outlet Dimensions (Side b): 470 mm x 470 mm.
- Length (t): 1,000 mm.
- Material: 3 mm (or 2 mm carbon steel plate) as available.

5. Transmission System:

- Type: *Timing Pulley* with *V-Belt belt*.
- Pulley Diameter (dp): 22 mm (1:1 Ratio).
- Distance between shafts (C): Planned 230 mm.

Testing Scheme

The test is carried out by assembling all components. The air from the blower enters through the contraction chamber -> passes through the turbine in the turbine box -> through the test section -> exits via the diffuser.

The rotation of the turbine is measured with a tachometer. Mechanical power is transmitted via belt to the generator. The output of the generator (Volt, Ampere) is measured with a multimeter. Data collection is carried out for 10 seconds to obtain the average value.

RESULTS AND DISCUSSION

Calculation and Structural Analysis of Wind Tunnel Body

The first step in ensuring the feasibility of the tool is to verify that the structure is capable of withstanding both physical and operational loads. The analysis was carried out through manual calculations and computer simulation (FEA).

Calculation of Dimensions and Physical Load

Based on geometric measurements, the surface area of the material used for each component is calculated as follows:

- Contraction Space: Using the trapezoidal area formula, the total surface area of the plate = 0.2025 m^2 is obtained.
- Box Turbin: The surface area of the acrylic used = 0.17 m^2.
- Test Section: Beam surface area (without front/rear cover) = 0.7603 m^2.
- Diffuser: Trapezoidal surface area = 0.36 m^2.

The total area of the steel plate material (carbon steel) is the combined Diffuser and Contraction Chamber: $0.2025 + 0.36 = 0.5625\ m^2$.

The total area of acrylic material is the combined Box Turbine and Test Section: $0.17 + 0.7603 = 0.9303\ m^2$.

With a plate thickness (t) of 2 mm (0.002 m) and a material density (ρ) of steel = 7,850 kg/m^3 and acrylic = 1,180 kg/m^3, the total weight of the structure is calculated:

- Steel Weight: $0.5625 \times 0.002 \times 7.850 = 8.83\ kg$.
- Acrylic Weight: $0.9303 \times 0.002 \times 1.180 = 2.19$ kg
- Total Weight: $11.02\ kg$.
- Total Gravity (W): $11.02 \times 9.81 = 108.11\ Newton$.

This force of 108.11 N is the basic load applied in voltage analysis.

Maximum Voltage Analysis: Manual vs FEA

Stress is the main indicator of potential failure. The analysis compared simple manual calculations ($\sigma = F/A$) with the results of more complex FEA simulations (using *the Von Mises* criteria).

Table Maximum Voltage Comparison

Component	Manual Voltage (N/m²)	FEA (Von Mises) Voltage (N/m²)	Material Yield Limit (N/m²)	Status
Contraction Chamber	540,55	4.386,31	282.685.049	SAFE
Box Turbine	635,94	2.854,64	45.000.000	SAFE
Test Section	142,25	251,57	45.000.000	SAFE
Diffuser	300,31	417,55	282.685.049	SAFE

Analysis:

The results of manual calculations show a very low voltage value. However, the results of the FEA simulation show a higher voltage value (e.g. in the Contraction Chamber: 4,386 N/m² vs 540 N/m²). This disparity occurs because FEA takes into account stress concentrations in complex geometries, sharp angles, and bolt base effects, which are ignored in a simple manual formula. Nevertheless, the highest FEA stress value (4,386 N/m²) is still very far below the yield strength limit (Yield Strength ~282 Million N/m²). This is confirmed by FEA visualization (dominant blue) which indicates the structure is working within a very safe elastic range.

Strain and Displacement Analysis

In addition to the voltage, physical deformation is also evaluated to ensure the rigidity of the tool.

- Contraction Space: Max stretch 0.0029 mm. This microscopic deformation will not affect airflow.
- Box Turbin: Max *displacement* 0.014 mm. As an acrylic component that resists the dynamic load of the turbine, this value is very small and guarantees that the turbine walls will not warp or vibrate excessively which may interfere with the rotation of the turbine.
- Diffuser: The strain is very small (0.000232 mm), showing extreme rigidity due to the use of steel plates.

Safety Factor Analysis

The safety factor (FOS) is the ratio of material strength to workload.

Table: Safety Factor Values of FEA Simulation Results

Component	Safety Factor Minimum	Interpretation

Contraction Chamber	64.447,09	Over-engineered structure
Box Turbine	15.763,83	Highly Safe for plastic/acrylic materials
Test Section	3.735,58	Safe, the most rational value
Diffuser	677.006,94	Extreme strength, potential for material waste

Discussion:

The FOS value of reaching hundreds of thousands (on the Diffuser) shows that this design is very conservative. Technically, this means that it is almost impossible for the tool to experience structural failure due to simulated loads. However, from a material efficiency standpoint, a 2 mm steel plate may be too thick for low aerodynamic loads (2.18 m/s). Plate thickness may be reduced in the future to save cost and weight without significantly sacrificing safety.1

Performance Analysis of Transmission and Power Generation Systems

Once the integrity of the *body structure* is ensured to be safe, the analysis is continued on the performance of the electromechanical system installed in it. The main focus is the efficiency of energy transfer from wind -> turbines -> transmission -> generators.

Savonius Turbine Operational Data

Tests were carried out on two turbine configurations: 3 spoons and 4 spoons, with consistent reference wind speeds.

1. Rotational Speed (RPM)

Measurements using a tachometer show:

- 3-Blade Turbine: 122.9 RPM.
- 4-Blade Turbine: 137.3 RPM.

The 4-blade turbine rotates faster. This indicates that the addition of the number of blades to the Savonius design in the wind tunnel increases the efficiency of capturing the *drag* force of the concentrated airflow.

2. Torque and Mechanical Power

Torque (T) is calculated based on the turbine mass and gravitational acceleration on the arm of effective moment.

- 3 Blade Turbine: Mass 0.76 kg -> Torque 1.0651 Nm. Mechanical Power

(P{mek}) = 13.7 Watts.

- 4 Spoon Turbine: Mass 0.96 kg -> Torque 1.3453 Nm. Mechanical Power (P{mek}) = 19.33 Watts.

The increased number of blades not only increases RPM but also significant torque, resulting in almost 41% greater total mechanical power on the 4-blade variant.

Electrical Output and System Efficiency Analysis

Electrical data (Voltage and Current) was taken using a multimeter for 10 seconds.

Turbine and Transmission Performance Comparison Table

Parameters	3 Tbsp Turbine	4 Tbsp Turbine
Average Voltage (V)	3.6 Volt	5.6 Volt
Average Current (I)	1.0 Amps	3.0 Amps
Electrical Power (Pout)	3.6 Watt	16.8 Watts
Mechanical Power (Pin)	13.7 Watt	19.33 Watts
Conversion Efficiency	~26.2%	~86.9%

Analysis:

There is a noticeable difference in efficiency. A 4-blade turbine is capable of converting almost 87% of mechanical power into electricity, while a 3-blade turbine is only 26%.

The cause of inefficiency in a 3-blade turbine is most likely Low Initial Torque. DC generators have an internal swivel resistance (cogging torque). A 3-blade turbine, with a torque of 1.06 Nm, may struggle to cope with the static friction of transmission and generator systems, so much energy is wasted as frictional heat. In contrast, a 4-blade turbine with a torque of 1.34 Nm has enough power margin to spin the generator at its optimal working point.

Evaluation of Belt Transmission System (V-Belt)

The transmission system uses *a 1:1 ratio* pulley timing and *a V-belt*.

- Belt Length Calculation: Based on the distance between the shafts (C) 230 mm and the *pulley diameter* of 22 mm, the ideal belt length is calculated. However, the belt used has an actual length of 528 mm.
- Slack Problem: A reverse calculation shows that with a 528 mm belt, the actual distance between shafts becomes about 229 mm (1 mm less than the 230 mm design). This lack of distance causes the belt to become loose

(*slack*).

- Impact: This loosening has the potential to cause slip, especially on 3-blade turbines whose rotation is more unstable. This slip reduces the linear speed of the belt (measured only 0.14 - 0.15 m/s) and is one of the main factors in power loss.[1]
- Transmission Ratio: The use of a 1:1 ratio means that the generator's RPM is equal to the turbine's RPM (max 137 RPM). For small size DC generators, this RPM is relatively low to produce high voltage. The use of *a step-up* ratio (e.g. 1:2) is recommended to increase the output voltage in the future.

CONCLUSIONS AND SUGGESTIONS

Conclusion

This integration of structural design research and transmission systems resulted in several key conclusions:

1. Absolute Structural Safety: The design of the open type wind tunnel body (contraction chamber, turbine box, *test section*, *diffuser*) using carbon steel and acrylic is proven to be very safe. FEA analysis showed a minimum *Safety Factor* value of 3.7 in the *Test Section* and >600,000 in the *Diffuser*. The maximum working voltage of the structure (4,386 N/m^2) is only a fraction of the material capacity, guaranteeing the absence of mechanical failures during operation.
2. 4-Spoon Design Validation: In the context of this wind tunnel, the 4-spoon Savonius turbine proved to be far superior to the 3-spoon. The 4-blade variant produces 16.8 Watts of electrical power with a system conversion efficiency of ~87%, compared to the 3-blade variant which only produces 3.6 Watts with an efficiency of ~26%.
3. Transmission Inefficiency: The designed 1:1 *pulley transmission system* suffers from dimensional precision constraints. The belt length of 528 mm is not perfectly synchronized with the shaft pitch of 230 mm, causing loosening and slippage that is detrimental to power transfer efficiency.
4. Prototype Feasibility: Overall, *the* designed wind tunnel body is suitable for use as a standard laboratory test equipment due to its robustness. However, the power generation system in it requires improvements in the transmission sector to achieve optimal results.

Suggestion

For the sake of improved tool performance and further research, it is recommended:

1. Belt Dimension Optimization: Using *a belt tensioner* mechanism or fine-

tuning the shaft spacing to fit the standard belt length, to eliminate slip.

2. Transmission Ratio Modification: Replace *the generator pulley* with a smaller diameter (*step-up* ratio) to increase the generator RPM, so that the output voltage can increase even at low wind speeds.
3. Reduction of Structural Materials: Given *the very high* Safety Factor of *the Diffuser* and the *Contraction Chamber*, further research may use thinner plates (e.g. 1 mm) for cost and weight efficiency.
4. Advanced Aerodynamic Analysis: Performed a CFD (*Computational Fluid Dynamics*) simulation to visualize flow patterns within the *turbine box* to understand why a 4-blade turbine works much more effectively aerodynamically.

Bibliography

Aditya, V., Alchalil, A., Asnawi, A., & Rahman, A. (2023). Analisa Indikator Kinerja Terowongan Angin Rangkaian Terbuka (Open Circuit Wind Tunnel) Tipe Subsonic. *Malikussaleh Journal of Mechanical Science and Technology*, *7*(2), 120. https://doi.org/10.29103/mjmst.v7i2.13658

Aji Saputra, R., Indra Partha, C. G., & Sukerayasa, I. W. (2021). Rancang Bangun Sistem Pemanen Energi Angin Exhaust Fan Turbin Angin Sumbu Horizontal Dengan Pengarah Angin (Wind Tunnel). *Jurnal SPEKTRUM*, *8*(2), 229. https://doi.org/10.24843/spektrum.2021.v08.i02.p26

Daingah, L. M., Tangkuman, S., & Punuhsingon, C. (2022). Perancangan Gearbox Turbin Angin Savonius Tipe-L Untuk Pembangkit Listrik Pada Rumah Tinggal. *Jurnal Poros Teknik Mesin Unsrat*, *11*(1), 67.

Hidayat, M. F., & Xaverius, F. (2022). Rancang Bangun Terowongan Angin Kecepatan Rendah Tipe Terbuka Sederhana dengan Smoke Generator Sebagai Visualisasi Aliran Udara Untuk Alat Pratikum. *Jurnal Kajian Teknik Mesin*, *7*(2), 63–72. http://journal.uta45jakarta.ac.id/index.php/jktm/article/view/6459%0Ahttp://journal.uta45jakarta.ac.id/index.php/jktm/article/download/6459/2282

Maulana, E., Djatmiko, E., Mahandika, D., & Putra, R. C. (2021). Perancangan Pembangkit Listrik Tenaga Angin dengan Turbin Angin Savonius Tipe-U untuk Kapasitas 100 W. *Jurnal Asiimetrik: Jurnal Ilmiah Rekayasa & Inovasi*, *3*, 183–190. https://doi.org/10.35814/asiimetrik.v3i2.2164

Pendidikan, J., & Arab, B. (2022). *Vol. 1 No. 2 Desember 2022*. *1*(2), 12–25.

Pradana, M. R. B., Anam, C., Yuniwati, I., Lazuardi, M., & Sari, E. N. (n.d.). *ANALISIS KEKUATAN BEARING PADA MESIN GRANULATOR TERHADAP PEMBEBANAN STATIS MENGGUNAKAN METODE FINITE ELEMENT ANALYSIS (FEA)*. *24*(2), 45–49.

Pradana, M. R. B., Anam, C., Yuniwati, I., Lazuardi, M., & Sari, E. N. (n.d.).

Rey, P. D., Aziz, A., Hermawan, D., Muhammad,), Nurkhozin, F., Teknik, J., Fakultas, M., Dan, S., Universitas, T., As-Syafi'iyah, I., Besar, B., Konversi, T., & Bppt, E. (2020). Webinar Nasional Cendekiawan Ke 6 Tahun 2020. In *KOCENIN Serial Konferensi* (Issue 1).

Rifai, T., Gunadi, G. G. R., & Ridwan, E. (2021). Rancang Bangun Pembangkit Listrik Tenaga Bayu (Angin) Mikro Turbin Savonius pada Jalan Tol Jatiasih. *Jurnal Mekanik Terapan*, *2*(2), 82–88. https://doi.org/10.32722/jmt.v2i2.4423

Suryady, S., & Sapto, A. D. (2024). *Analisis Pembebanan Statis terhadap Rangka Mesin Alat Pengaduk untuk Adonan Donat menggunakan Sofware FEA Jurnal Teknik Mesin : Vol . 13 , No . 1 , Februari 2024 ISSN 2549-2888*. *13*(1), 22–29.