COMPARISON BETWEEN THE DIFFERENT TYPES OF ROTOR BLADES FOR VERTICAL AXIS WIND TURBINE

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ABSTRACT

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Comparison between the different types of rotor blades for Vertical Axis Wind Turbine

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This research centres its attention on wind energy as a pivotal component in the global pursuit of renewable energy sources. It delves into the intricate domain of rotor designs prototypes, vital for capturing wind's kinetic energy and converting it into usable power for Vertical Axis Wind Turbines (VAWTs). The study thoroughly investigates rotor performance across a spectrum of wind speeds and scenarios, revealing the interplay between stiffness, flexibility, and adaptability. The primary objective of this research is to bridge the gap in knowledge by examining how rotors with unconventional materials perform.

It meticulously examines rotational speeds, Tip Speed Ratio, and Reynolds Number under varying wind velocities to evaluate the effectiveness of three rotor variations: Rigid, Flexible, and Semi-Flexible. The findings reveal distinctive performance characteristics for each rotor design. Notably, the Flexible rotor excels at lower wind speeds but encounters constraints at higher speeds, while the Semi-Flexible rotor demonstrates impressive stability across diverse wind conditions. Beyond technical insights, the study promotes advanced rotor designs, and consideration of economic and environmental impacts. It offers study's insights underscore the complexities of rigidity, flexibility and adaptability in rotor designs and offer significant implications for wind energy technology advancement. The research recommends exploring enhanced rotor designs, employing unconventional materials, geometrical innovations, and structural enhancements. Moreover, the study avenues for the further research, emphasizing aerodynamic characteristics, structural behaviour, and potential design optimization to elevate the efficiency and effectiveness of VAWTs in harnessing renewable energy.

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SYMBOLS AND ABBREVIATIONS

Roman Letters:

p: Pressure [bar, Pa]
qm: Mass flow rate [kg/s]
R: Gas constant [J/kg K]
T: Temperature [ºC, K]
x: Vapour content
U: Voltage [V]
V: Volume [m^3]
v: Specific volume [m^3/kg]
A: Swept Area [m^2]
D: Rotor Diameter [m]
H: Blade Height [m]
r: Blade radius [m]
d: Blade diameter [m]
Re: Reynolds number
ω (omega): Angular velocity [rad/s]
vc: Critical Velocity

Greek Letters:

ρ (rho): Air Density [kg/m^3]
μ (mu): Fluid Viscosity
λ (lambda): Tip Speed Ratio

ABBREVIATIONS

VAWT: Vertical Axis Wind Turbine
HAWT: Horizontal Axis Wind Turbine

Fn : Normal drag force

Ft: Tangential drag force

TSR: Tip Speed Ratio

FSI: Fluid-Structure Interaction

ABS Plastic: Acrylonitrile butadiene styrene

PLA: Polylactic acid

PSP: Pressure Sensitive Paints

RPM: Revolution per Minute

FPS: Frame Rates per Second

LED: Light Emitting Diode

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1 Introduction

1.1 Wind Turbines

A wind turbine is a mechanical mechanism that harness the kinetic energy and converts it to the form of electrical energy. It is the important source of renewable energy commonly used by many countries in the globe to produce clean, sustainable and cost-effective energy systems. Wind turbines consists of rotor blade which rotates when exposed to the wind. The rotor is connected to the generator. When the rotor starts rotating, the mechanical energy is transferred to the generator where the generator converts it to the electrical energy. The wind turbine is classified into two types, namely Horizontal Axis Wind Turbine (HAWT) and Vertical Axis Wind Turbine (VAWT). This thesis encompasses an in-depth analysis of the behaviour of the different types of prototype rotors for VAWTs. The major insight is to analyse and understand how rotors with unconventional materials behave when we run it through the same wind speed. The VAWT haven´t been in the centre of attention because of the many reasons while one of the main reasons being more expensive and it´s poor performance efficiency. The response of these rotors is insightful for many reasons such as performance improvement and cost-effectiveness. This research aims to address the limitations and challenges associated with VAWTs.

Previous studies concluded that VAWTs gets less attention due to the factors such as cost-effectiveness and efficiency whereas there is hardly any thorough examination of the behaviours of the rotors with un-conventional materials under similar conditions. Therefore, this study would fill that research gap and provide a deeper understanding of how such rotors perform. To address the problem, our main objective was to find out the answers to the following questions:

1) How do rotors with unconventional materials behave when exposed to the same wind speed?
2) What are the different measurement characteristics such as rotational speed, Reynolds number, Tip Speed Ratio, etc for the rotors?

3) Would it be possible to improve the VAWTs performance using unconventional materials?

1.2 Horizontal Axis Wind Turbines

Horizontal Axis Wind Turbines, also known as HAWTs are the most popular and widely used wind turbines around the globe in commercial- scale wind generations. The rotor shaft where rotor blades of the turbine are mounted is parallel to the ground. These turbines use lift force to rotate the blade. Due to the furling system, the rotor could be arranged perpendicular to the direction of wind so that the optimum energy could be extracted at the highest speed. HAWTs consist of a hub, main shaft, gear box, brake, high speed shaft and a generator at the top of the tower. Large, scaled wind turbines use auxiliary motors while smaller one uses simple wind vane (Elprocus, 2023). Auxiliary motors find application in accurately managing large wind turbines, particularly in industrial wind farms. These motors enable meticulous adjustments to the turbine's orientation, referred to as yaw control, ensuring direct alignment with the wind and optimizing energy generation. Conversely, smaller turbines commonly seen in residential areas adopt simpler methods. Utilizing an uncomplicated wind vane and tail fin, they passively align with the wind, ensuring the turbine rotor always faces the wind's direction and achieves peak energy conversion.

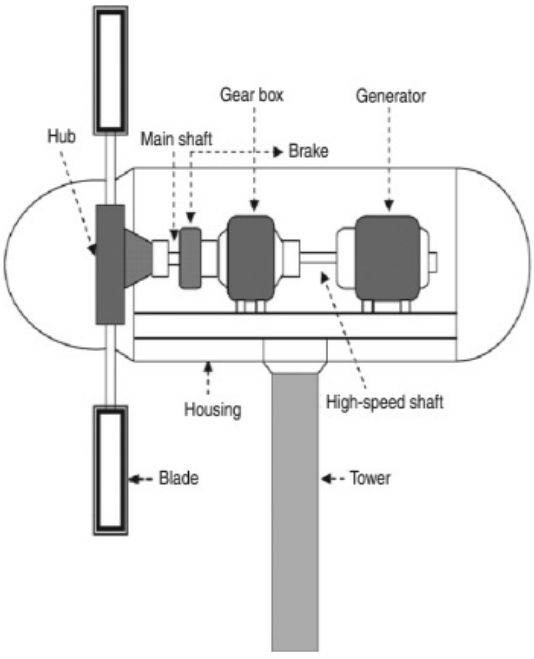

Fig 1: Section View of HAWT (Elprocus, 2023)

The major drawback of this turbine is that it requires a braking mechanism to decrease the speed of the rotor blades when the speed of the wind is too strong (Hau, 2013) . The noise is also another concern for HAWTs. The noise is quite strong; therefore, the population will be easily disturbed.

Although these limitations, HAWTs are continuously dominating the technology in the renewable energy industry because of its efficiency, performance, and scalability in large-scaled power generations.

1.3 Vertical Axis Wind Turbines

Vertical Axis Wind Turbines, also known as VAWTs is another type of wind turbine. It has the shaft of the rotor is mounted vertically, perpendicular to the ground. While HAWTs have a horizonal rotor shaft, VAWTs have their blades arranged around the centre of the vertical axis. All the major system components are situated at the bottom of the tower. The orientation of the VAWTs and the symmetricity of its blades makes it more feasible to catch the best wind in all directions It does not need to be oriented artificially to enhance the energy generations. The mechanical complexity of these systems is not so much than that of HAWTs. It reduces the need and complexity of the maintenance. As the main parts of the systems are on the ground level, all the maintenance could be done directly from the bottom. Also, because of the design where the blades are connected to both ends, it makes it less brittle as the stress is less in the blades (Nigam Dilip, 2019).

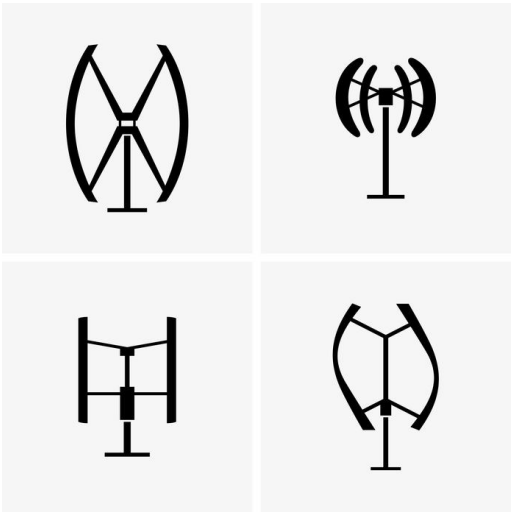

Fig 2: Vertical Axis Wind Turbines different designs (Arborwind, 2023)

VAWTs have seen less widespread adoption compared to HAWTs because of their durability, scalability, and reliability. As per the reports, coefficient of performance is also less in VAWTs than that of HAWTs (Nigam Dilip, 2019). However, ongoing technological advancement and research aims to address and improve the challenges, performance and cost-effectiveness of the VAWTs.

2 Literature Reviews

2.1 Overview

The researchers all over the globe are working on the advancement and betterment of the vertical axis to increase its overall conversion efficiency by reducing the drag losses. Savonius wind turbines are known as drag-type vertical axis wind turbines. It can also be identified as "S" shaped rotor designs. Rotation in these kinds of turbine is caused by the aerodynamic forces acting on its rotor blades by generating the difference in pressure between the advancing and returning blades (Hau, 2013). Normal drag force (Fn) acts perpendicular to the wall of the blades while tangential drag force (Ft) acts along the tangential direction of each blade (Khan, Bashar & Rahman, 2013). The schematic diagram is shown below with the components of the drag forces on each blade.

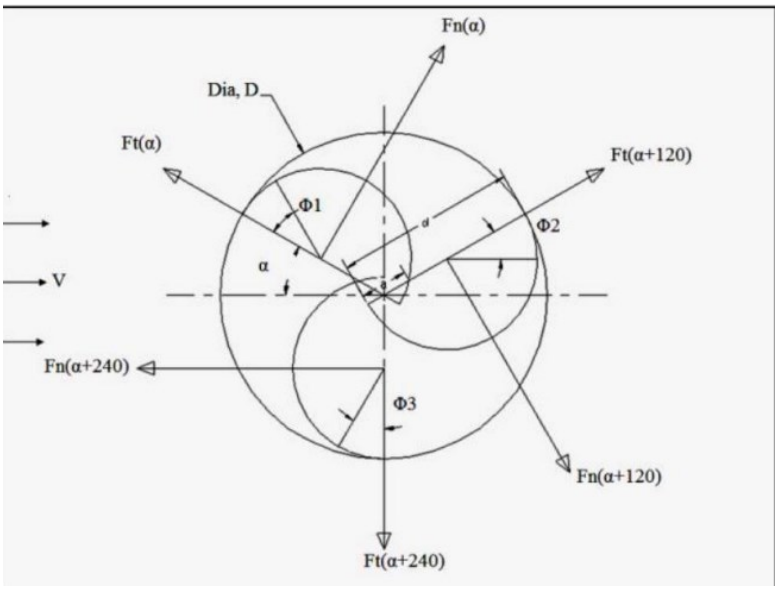

Fig 3: Schematic diagram of Savonius rotor with the drag force components (Khan, Bashar & Rahman, 2013)

A similar type of research was conducted by MacPhee, David William on University of California, San Diego where he submitted a dissertation on the topic "Flexible Blade Design for Wind Energy Conversion Devices". As the recent research showed that the flexible blades rotor design can increase the aerodynamic lift, reduce drags, and even delay stall for two-dimensional air foil sections, he developed a fully three-dimensional Fluid-Structure Interaction (FSI) solver and used it to simulate a flexible HAWT and VAWT rotors then later did the comparison between the experimental results.

To solve the decreased efficiency and operational envelope in small wind turbines, MacPhee purposed a "morphing blade concept" where he built the blades incorporating flexibility into the design process. He suggested that the flexibility lets the geometry of the rotor blades to adapt accordingly to the local wind conditions needing no control systems.

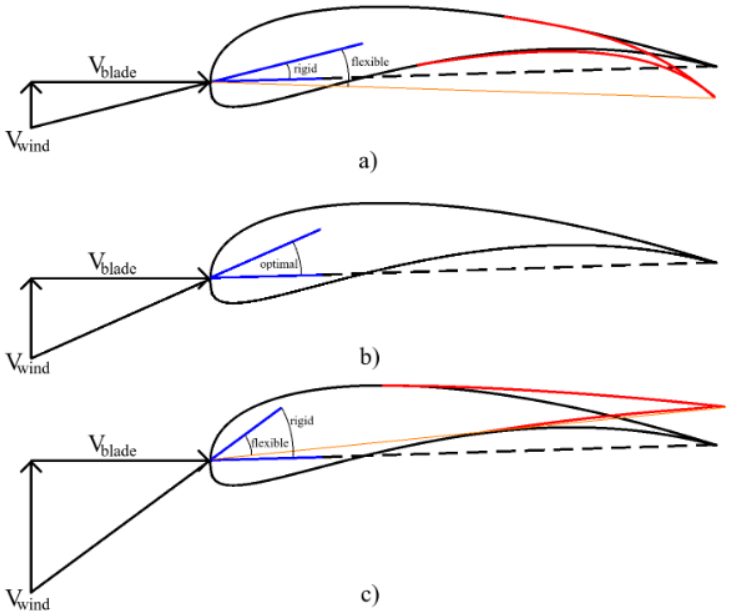

Fig 4: Morphing blade proposed operation (MacPhee, 2014).

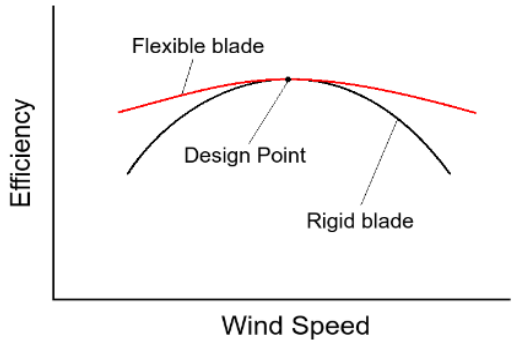

Fig 5: Rigid and proposed flexible blade performance curve (MacPhee, 2014).

2.2 Design and process.

To produce a geometrical identical blade, MacPhee designed two separate poured polyurethane injection moulding process to accommodate both rigid and flexible rotors. For the rigid blades, solid models were created and milled from acrylic sheets, with a base designed for attachment. The flexible blades used a two-part moulding process, attaching flexible material to a rigid spine made of solid polyurethane. The inner blade mould was used for pouring flexible material, like the rigid blade fabrication. Both blade types were cast and demoulded, The hub for blade assembly was 3D printed from ABS plastic, with markings for different pitch angles for comparison (MacPhee, 2014).

MacPhee arranged the test rig incorporated with a turbine shaft, torque sensor, and hydraulic brake. The main shaft was stabilized by bearings, preventing unwanted movement and safeguarding the toque sensor. Rubber couplings reduced vibration. The sensor recorded shaft torque and angular velocity for power calculation. Data was collected over 15 seconds and averaged to minimize errors (MacPhee, 2014).

2.3 Results and Conclusions

MacPhee, research aimed to compare the performance of flexible wind energy devices with traditional rigid ones. Key steps included experimental analysis of flexible horizontal-axis wind turbines and numerical simulations of flexible and rigid HAWTs and vertical axis wind turbine rotor types. Flexible HAWTs demonstrated improved torque, augmented power coefficients, and an expanded operational envelope. Flexible VAWTs showed increased power coefficients, torque efficiency, and potential for self-starting. The study indicated that flexible blade designs can enhance wind turbine efficiency and operational range, benefitting small-scale HAWTs and VAWTs without pitch control strategies. Further research was suggested to explore different material properties and blade configurations (MacPhee, 2014).

2.4 Motivation for the research

After studying this discretion, several potential gaps related to Flexible Vertical Axis Wind Turbine rotors were identified for the further exploration. While MacPhee's research highlighted the merits of flexible VAWT rotors in terms of torque efficiency and operational envelope expansion, their performance at even higher Tip-Speed Ratios (TSR) could be investigated to understand the behaviour, capabilities and limitations in extreme wind conditions. The dynamic response of the flexible blades, their deformation characteristics, and how the overall rotor performance is affected can be explored. The effect of material properties on performances with different material density, elastic modulus, and other properties could potentially impact the performance could be valuable for optimizing their design. Exploring the performance characteristics and efficiency improvements of the flexible rotor blades across a wider range of wind speeds would provide comprehensive understanding of their benefits. By addressing few of these gaps, I want to contribute to a more comprehensive understanding of the potential benefits, challenges, and practical implications of using flexible VAWT rotors in wind energy systems.

3 Methods

3.1 Designing and Modelling

In the beginning, a design of the wind turbine was modelled on the SolidWorks. The rotor diameter (D) was set to 200 mm. The blade diameter (d) was set to be 85 mm. The radius (r) of the blade was set 57.5 mm. The height of the blade was set 177 mm.

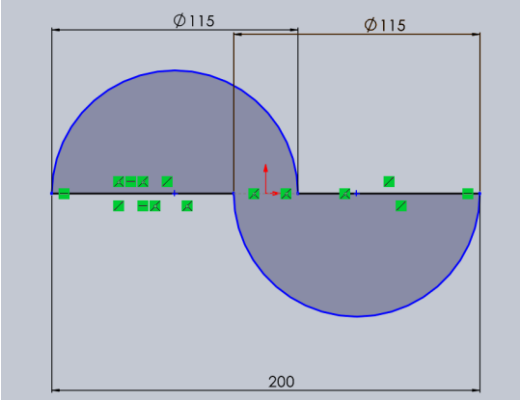

Fig 6: Sketch view of designed turbine

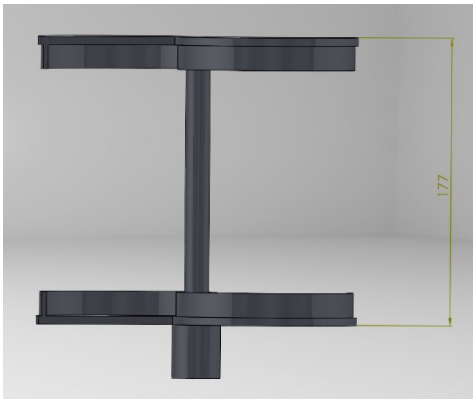

Fig 7: Sketch view of designed turbine

The above picture was the base for all three rotors we were building. As we were using the unconventional material for this research, the plan was to design all the three rotors: one to be printed completely as a whole (Rigid rotor), and the other two to be covered with Rayon rubber composite later after printing the base for the rotors. Among the two rotors, one design (Semi-flexible) had supports at the edges so that the rubber might not deform as much when we pass it through the high-speed wind and another one (Flexible) did not have any supports at all.

The design for the bottom was also modelled using SolidWorks with a plan to use two bearings which could hold and help the rotor rotate easily when passing through the wind. The rotor shaft would go inside the rotor blade and all the way down to the bottom of the turbine. Bolts would hold the shaft with the rotor above while bearings would hold the shaft at the bottom of the turbine. In a nutshell, the overall bottom would be bolted onto a strong and heavy metal plate to make it stable to get the optimum result when obtaining the measurements.

Fig 8: Semi-flexible rotor design (edge supports)

Fig 9: Rigid rotor design.

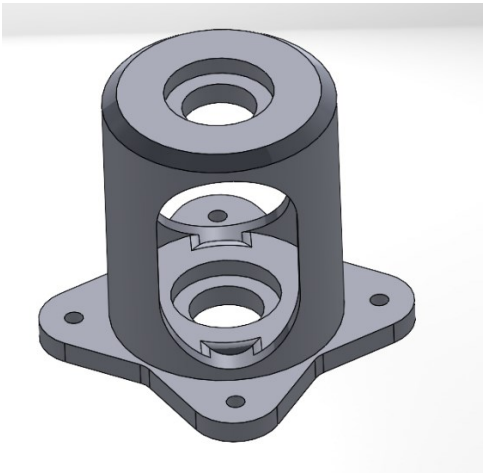

Fig 10: Bottom part of the turbine

Fig 11: Final design of the turbine

The total height of the bottom part is 120 mm. The thickness of the rotor shaft is 25 mm.

3.2 3D Printing

The design was then converted to .STL file from the SolidWorks. Then by using the application from the Prusa named **PrusaSlicer 2.6.0,** the brim and support were arranged so the printer could print it smoothly. PLA material was opted to print using the 60% infill with 0.15 mm Quality (modified) nozzle. It used around 309 grams of filament and took 1 day 10 hours and 34 minutes to print. The supports structures were arranged everywhere. Support structures play a critical role in 3D printing by safeguarding the precision of intricate designs

and overhanging elements. They provide temporary stability throughout the printing process, mitigating distortion and potential collapse. These supports effectively tackle the complexities arising from intricate geometries, guaranteeing accurate and top-notch printed results. The printer used was Original Prusa i3 MK3S & MK3S+.

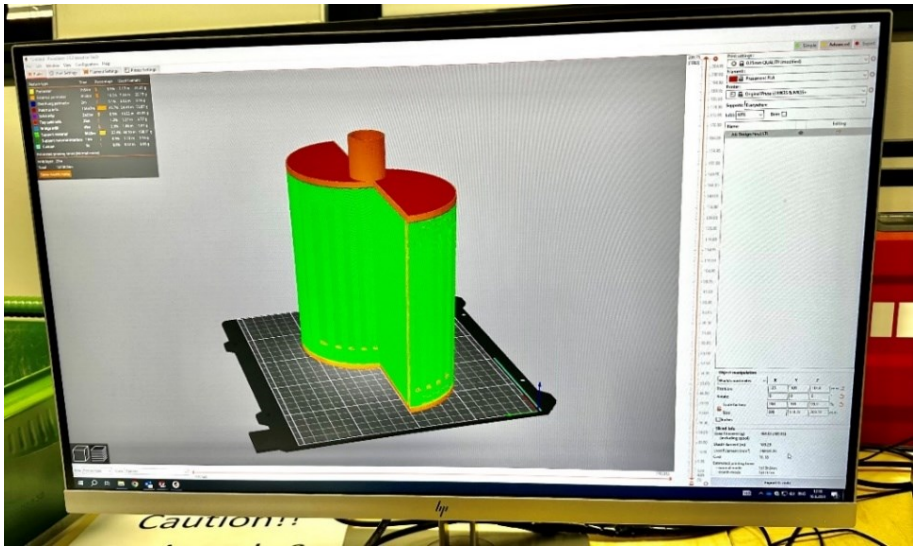

Fig 12: The settings used for printing the rotor blade.

Fig 13: Original Prusa i3 MK3S & MK3S+ 3D printer (Prusa, 2022)

After the completion of the printing, the Flexible and semi-flexible rotor was covered with the Rayon Rubber Composite (mixture of cellulose fiber and synthetic rubber) using epoxy glue. Its thickness was 1mm. The rubber was then dried for few hours and was assembled.

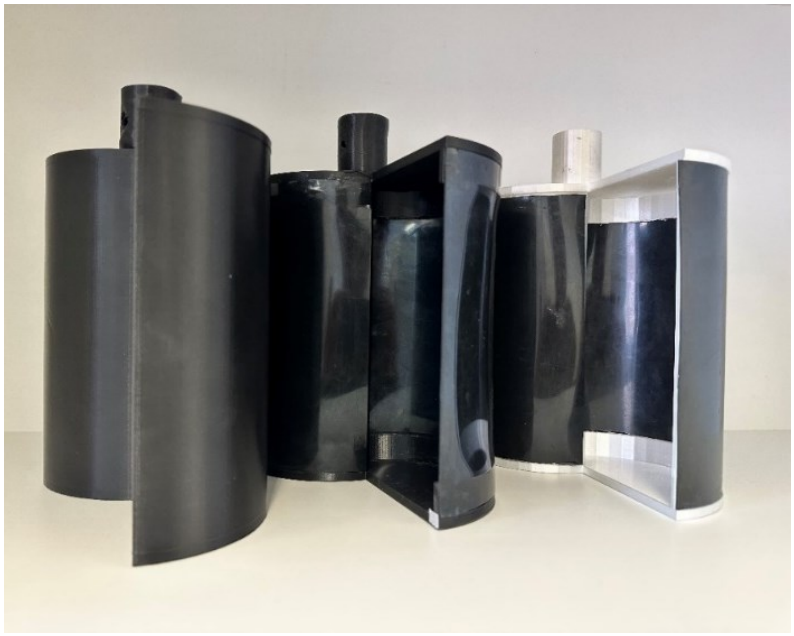

Fig 14: Rigid rotor, Flexible rotor & Semi-Flexible rotor (left to right)

While assembling, based on the thickness of the shaft and the estimated speed of rotation of the turbine, 16005 ball bearings were selected as bearings. The outer diameter of the bearing is 47 mm, and the inner diameter is 25 mm.

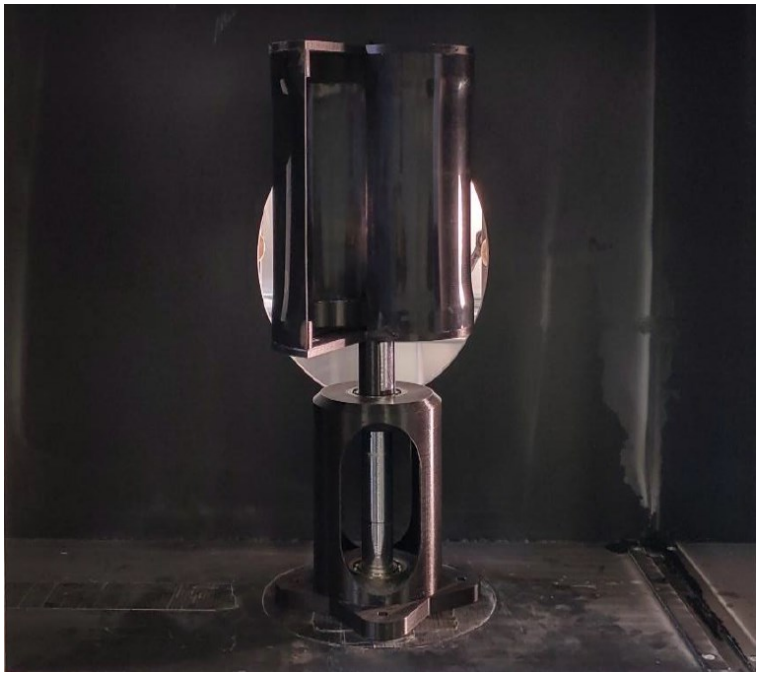

Fig 15: Final Assembly of the wind turbine

3.3 Wind Tunnel

A wind tunnel is a system used to test and analyse the stationary objects inside a tube, by blowing the air around to understand the aerodynamic effects in the objects. Wind tunnels vary in sizes and can be over 30 m. It can have air moving at the speeds from a light breeze to hypersonic velocities. Usually, huge fans blow the air through the tunnels, while prototype is clamped properly at rest. The speed of the wind can be easily changed according to the requirements. The angle of attack (angle between the incoming airflow and the reference line of the object being tested) for the wind can also be changed which significantly influences the aerodynamic forces acting on the object. The major merit of the wind tunnel testing is that it helps assess the structural integrity and safety of objects under different aerodynamic loads. For example: if an aeroplanes or wind turbines needs to be tested, it is easier to test it the wind tunnel as it involves low risk and offers controlled and repeatable environment. The objects performance can be easily optimized, tested, validated, studied, analysed for noise and aerodynamic efficiencies, and can be repeated under precise conditions to collect the accurate data. As air is transparent, for the flow visualization different kinds of methods are used to observe the air flow. The most used methods are smoke, CO2, pressure sensitive paints, etc.

For this prototype, the rotational speed was tested using the wind from the wind tunnel. The measurements were taken from speed of the wind ranging from 3 m/s to 6 m/s. After clamping the wind turbine inside the wind tunnel, the lid of the tunnel was enclosed using transparent acrylic sheets and locked properly so that there is as less impact of the external environment as possible. A very high-speed resolution camera from Phantom known as Phantom Miro M310 12-28 VDC was used to record and detect the behaviour and the deformation of the wind rotors when passing it through the different wind speeds.

Tachometer was used to measure the rotational speed which showed the result in revolution per minute (rpm). For the more precise data, the measurement was taken in the interval of every 10 seconds for in total of 60 seconds at each speed. Later, the average was calculated using excel sheet.

3.4 Excel Calculations

Rotational speed is the speed at which an object revolves around its own axis per unit time. Unlike linear speed, rotational speed is the number of rotations made by an object in a period. Rotational speed can be measured in two different units: revolutions per minute (rpm) and radians per second (rad/s). RPM represents the number of full revolutions a rotating object makes in one minute around a fixed axis. While radians per second is a unit of angular velocity based in the International Systems of Units known as SI units. It measures the angle covered by the rotating object in radians per second. One radian is equal to the angle subtended at the centre of a circle by an arc equal in length to the radius of the circle.

In the excel sheet, first rotational speed (rpm) was converted to rotational speed (rad/s). The equation used to do so is mentioned below:

$$Rotational\ Speed\ \left(\frac{rad}{s}\right) = 2 \cdot \pi\ \frac{rad}{s} \cdot \frac{RPM}{60} s \qquad (1)$$

The rotational speed of the wind turbines may not be constant all the time. Wind speed and other factors affects the rotational speed. Due to the advancement in technology, the turbines can now adjust their rotational speed to optimize the efficiency while ensuring the safety prerequisites of the overall components of the turbines. The low-speed shaft connected to the gearbox is responsible for increasing the rotational speed of the turbine to the required level for the generator.

The wind turbines used in small scaled or residential level usually has different rotational speed as it depends upon the design and purpose. Large–scaled turbines supposedly rotate at around 20 RPM, while smaller turbines rotate at around 400 RPM. The large-scaled turbines especially need low speed shaft connected in the gearbox as it can increase the rotational speed up to around 1200-1800 RPM with the help of gearbox which can then transfer the energy to the high-speed shaft driving the electrical generator to produce electricity. The gearbox ratio determines the number of revolutions required on the low-speed shaft to achieve one complete revolution of the high-speed shaft.

Usually, the gearbox ratio falls within the range of approximately 50 to 100 revolutions on the low-speed shaft for each complete revolution of the high-speed shaft (which is 50:1). (Action Renewables, 2019)

Tip Speed Ratio also known as TSR is one of the major factors in wind turbine designs. It is the ratio between the wind speed and the tangential speed of the tips of the wind turbine blades. Mathematically, TSR can be portrayed as:

$$TSR\ (\lambda) = \frac{(Tip\ Speed\ of\ the\ blade)}{Wind\ Speed} \qquad (2)$$

Tip speed of the blade is calculated as $\omega\ times\ R$ where: ω is the rotational speed of the rotor in radians/second and R is the rotor radius in metres. Therefore, rewriting the equation for TSR, we get:

$$TSR\ (\lambda) = (\omega * R)/v \qquad (3)$$

where v is wind speed in metres/seconds. Wind turbines these days are designed in such a way to get the optimal tip speed ratios to generate the maximum power from the wind. When the rotors of the turbines spin at slower speed, the wind can easily pass in between the rotor blades. This results in not enough force produced and therefore not giving it enough power to generate energy. While, when the rotors of the turbine spin at optimum speed, enough force is generated by the blades on the shaft generating the more energy. But, when the rotor speeds very fast, the gaps between the blades when rotating will be very small because of the high-speed wind and it will act like a solid wall to the wind. This phenomenon can also be addressed as turbulence. As the blades produce turbulence when spinning too fast, the blades itself is likely to hit the turbulence causing several effects such as reduced aerodynamic efficiency, increased load and stresses, increased vibration and noises, yaw misalignments, potentially damaging the structural integrity of the wind turbines.

For the VAWTs, the concept of TSR is slightly different compared to HAWTs as the design and operation of the VAWTs is different. In VAWTs, TSR refers to the linear speed of the outermost point of the blades as it rotates while wind speed refers to the wind approaching the turbine. VAWTs generally operate at lower TSR because increase in TSR could lead to increased aerodynamic losses and overall losses in efficiency of the VAWTs. Knowing the TSR of the turbine helps in maximizing the power output and efficiency of the turbine. A perfect tip speed ratio helps in generating the desired energy efficiently. To find the perfect Tip Speed ratio, the formula below has been empirically proven:

$$\lambda = \frac{4\pi}{n} \qquad (4)$$

where n is number of blades. (Minnesota Municipal Power Agency, 2015)

Reynolds number is the dimensionless quantity widely used in fluid mechanics to characterize the flow of a fluid in different situations by measuring the ratio between inertial and viscous forces. Reynolds number gives valuable insights into the behaviour of fluids in various systems such as predicting flow regime, innovative designs, drag and lift predictions, heat transfer analysis, turbulence analysis, different medium flows, aero and hydrodynamics and many more.

Critical velocity (v_c) is a term connected with Reynolds number. When the fluid is flowing through a small velocity, fluid travels in streamline (laminar) motion but once the velocity is increased to a certain limiting value, motion becomes turbulent. So, that limiting velocity (between streamline and turbulent flow) is known as critical velocity. The critical velocity depends upon the coefficient of viscosity of fluid (η), density of the fluid (ρ), and lateral dimension (r) of the tube in which fluid is flowing.

The equation for critical velocity (v_c) can be expressed as:

$$v_c = k * \eta/(\rho * r) \qquad (5)$$

where the above expression for the critical velocity is known as Reynolds formula and the constant k is known as Reynolds number. For the wind turbines, Reynolds formula can be written as:

$$Re = (\rho * D * v)/\eta \qquad (6)$$

where Re is Reynolds number, and D is the diameter of the rotor (Harihar Paudyal et al., 2078).

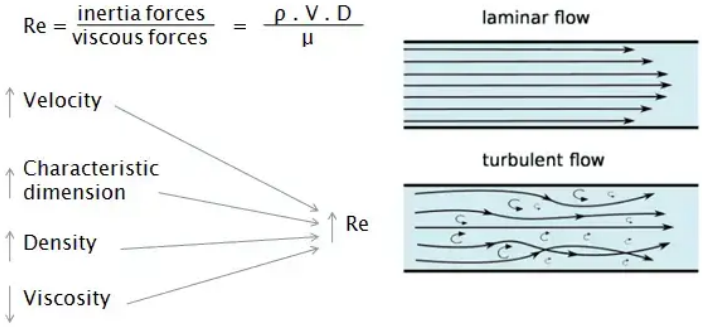

Fig 16: Laminar and Turbulent flow (Nuclear Power, 2023)

If Re < 2000: The flow is laminar as the fluid flows in smooth, parallel layers and almost no mixing. This type of flow is predictable.

If 2000 < Re < 4000: The flow is flowing at critical velocity (Transitional Regime), it has a property of both laminar and turbulent. It can vary situationally and is extremely difficult to predict.

If Re > 4000: The flow is called turbulent which is chaotic, unpredictable and mixes significantly.

In engineering and design, studying and understanding the Reynolds number plays a significant role for various applications, such as determining the flow in the pipes or in an air foil, selecting best fan designs, and analysing the aerodynamics of the aircrafts, vehicles, or wind rotor blades. This helps in increasing the overall efficiency of the objects ensuring the safe operation.

Viscosity mentioned above is the property of fluid which opposes the direction of relative motion of fluid due to the internal friction (tangential force) between the different layers is called viscosity. According to the newton's law of viscosity, the coefficient of viscosity of fluid (η) is defined as the viscous force acting per unit area of the layer having unit velocity gradient perpendicular to the direction of the flow of the liquid. The unit of coefficient of viscosity is $kgm^{-1}s^{-1}$. The viscous force is always negative as it always acts in opposite direction to the flow of the fluid (Harihar Paudyal et al., 2078). In fluid dynamics, viscous force can be elaborated using a concept of shear stress. In simple word, the faster the motion of the fluid velocity is, the higher the shear stress will be and consequently, the higher the viscous force. Viscous force directly affects the drag experienced by the bodies when in motion through the fluids. Minimizing, optimizing and controlling the viscous force is extremely important in most of the cases for optimizing the systems efficiency and reducing the overall energy consumptions.

In the excel file, the following values were used for the calculations:

D, Diameter of the rotor = 200 mm	r, radius of the blade = 57.50 mm
d, Diameter of the blade = 85 mm	H, height of the blade = 177 mm

The pressure (hPa), and the temperature ($°C$) were measured on the days of the measurements. Air dynamic viscosity ($Pa.s$) and density of the fluid (ρ), was calculated from the website (Omni Calculator sp. z o.o., 2023).

4 Results

4.1 Data Interpretation

After the experiment, the results were quite astonishing. Rigid rotor somehow behaved the same as we expected but the Flexible and Semi Flexible rotor behaved well beyond our expectations. The data for all the rotors below was collected on June 28th, 2023, under the normal environmental conditions where Pressure (P): 1011 hpa, Temperature (T): 24.2 °C, Air Dynamic Viscosity (μ): 1.833 *10^-5 Pa*s, and Density (ρ): 1.18447 kg/m^3. The total calculations of the data are attached below:

Rigid Rotor Data

Table 1: All measurements and average at 3.5 m/s

Velocity(m/s)	Rotational Speed (RPM)	Rotational Speed (rad/s)	Tip Speed Ratio (TSR)	Reynolds Number (Re)
3.60	170.00	17.80	0.28	46526
3.59	170.00	17.80	0.29	46397
3.60	170.00	17.80	0.28	46526
3.59	170.00	17.80	0.29	46397
3.56	170.00	17.80	0.29	46009
3.55	170.00	17.80	0.29	45880
3.58	170.00	17.80	0.29	46289

Table 2: All measurements and average at 4 m/s

Velocity(m/s)	Rotational Speed (RPM)	Rotational Speed (rad/s)	Tip Speed Ratio (TSR)	Reynolds Number (Re)
4.01	220.00	23.10	0.33	51825
4.00	220.00	23.10	0.33	51695
4.00	220.00	23.10	0.33	51695
4.01	220.00	23.10	0.33	51825
4.00	220.00	23.10	0.33	51695
4.01	220.00	23.10	0.33	51825
4.00	220.00	23.10	0.33	51760

Table 3: All measurements and average at 5 m/s

Velocity(m/s)	Rotational Speed (RPM)	Rotational Speed (rad/s)	Tip Speed Ratio (TSR)	Reynolds Number (Re)
5.01	330.00	34.60	0.39	64748
4.99	330.00	34.60	0.39	64490
5.01	330.00	34.60	0.39	64748
5.00	330.00	34.60	0.39	64619
5.01	330.00	34.60	0.39	64748
5.04	330.00	34.60	0.39	65136
5.01	330.00	34.60	0.39	64748

Table 4: All measurements and average at 6 m/s

Velocity(m/s)	Rotational Speed (RPM)	Rotational Speed (rad/s)	Tip Speed Ratio (TSR)	Reynolds Number (Re)
5.99	430.00	45.00	0.43	77413
5.98	430.00	45.00	0.43	77284
5.96	430.00	45.00	0.43	77026
5.96	430.00	45.00	0.43	77026
6.02	440.00	46.00	0.44	77801
6.01	440.00	46.00	0.44	77672
5.98	433.30	45.30	0.44	77371

Flexible Rotor Data

Table 5: All measurements and average at 3.5 m/s

Velocity(m/s)	Rotational Speed (RPM)	Rotational Speed (rad/s)	Tip Speed Ratio (TSR)	Reynolds Number (Re)
3.50	190.00	19.89	0.32	45069
3.51	190.00	19.89	0.33	45198
3.53	200.00	20.94	0.34	45455
3.5	190.00	19.89	0.32	45069
3.53	200.00	20.94	0.34	45455
3.54	190.00	19.89	0.32	45584
3.52	193.30	20.25	0.33	45305

Table 6: All measurements and average at 4.0 m/s

Velocity(m/s)	Rotational Speed (RPM)	Rotational Speed (rad/s)	Tip Speed Ratio (TSR)	Reynolds Number (Re)
4.03	250.00	26.20	0.37	51894
4.02	250.00	26.10	0.37	51765
3.96	240.00	25.10	0.37	50993
3.96	240.00	25.10	0.36	50993
3.95	240.00	25.10	0.37	50864
3.98	240.00	25.10	0.37	51250
3.98	243.30	25.50	0.37	51293

Table 7: All measurements and average at 5 m/s

Velocity(m/s)	Rotational Speed (RPM)	Rotational Speed (rad/s)	Tip Speed Ratio (TSR)	Reynolds Number (Re)
5.06	350.00	36.70	0.42	65157
5.07	350.00	36.70	0.42	65286
5.05	350.00	36.70	0.42	65028
5.08	350.00	36.70	0.42	65414
5.07	350.00	36.70	0.42	65285
5.03	350.00	36.70	0.42	64770
5.06	350.00	36.70	0.42	65157

Table 8: All measurements and average at 6 m/s

Velocity(m/s)	Rotational Speed (RPM)	Rotational Speed (rad/s)	Tip Speed Ratio (TSR)	Reynolds Number (Re)
6.03	430.00	45.00	0.42	77648
6.04	430.00	45.00	0.42	77777
5.99	430.00	45.00	0.43	77133
5.97	430.00	45.00	0.43	76875
5.97	430.00	45.00	0.43	76875
6.00	430.00	45.00	0.43	77261
6.00	430.00	45.00	0.43	77262

Semi-Flexible Rotor Data

Table 9: All measurements and average at 3.5 m/s

Velocity(m/s)	Rotational Speed (RPM)	Rotational Speed (rad/s)	Tip Speed Ratio (TSR)	Reynolds Number (Re)
3.48	180.00	18.80	0.30	44757
3.54	180.00	18.80	0.30	45529
3.53	180.00	18.80	0.30	45400
3.48	180.00	18.80	0.31	44757
3.48	180.00	18.80	0.31	44757
3.45	180.00	18.80	0.31	44371
3.49	180.00	18.80	0.31	44928

Table 10: All measurements and average at 4 m/s

Velocity(m/s)	Rotational Speed (RPM)	Rotational Speed (rad/s)	Tip Speed Ratio (TSR)	Reynolds Number (Re)
4.00	250.00	26.18	0.38	51445
4.04	250.00	26.18	0.37	51959
4.03	250.00	26.18	0.37	51831
4.12	260.00	27.23	0.38	52988
4.06	250.00	26.18	0.37	52216
4.03	250.00	26.18	0.37	51831
4.04	251.67	26.35	0.37	52045

Table 11: All measurements and average at 5 m/s

Velocity(m/s)	Rotational Speed (RPM)	Rotational Speed (rad/s)	Tip Speed Ratio (TSR)	Reynolds Number (Re)
5.04	350.00	36.70	0.42	64820
5.06	350.00	36.70	0.42	65078
5.05	350.00	36.70	0.42	64949
5.06	350.00	36.70	0.42	65078
5.08	350.00	36.70	0.42	65335
5.04	350.00	36.70	0.42	64820
5.05	350.00	36.70	0.42	65013

Table 12: All measurements and average at 6 m/s

Velocity(m/s)	Rotational Speed (RPM)	Rotational Speed (rad/s)	Tip Speed Ratio (TSR)	Reynolds Number (Re)
6.01	460.00	48.17	0.46	77296
5.98	460.00	48.17	0.46	76910
6.00	460.00	48.17	0.46	77167
5.98	460.00	48.17	0.46	76910
5.99	470.00	49.21	0.47	77039
6.03	460.00	48.17	0.46	77553
5.99	461.67	48.34	0.46	77146

4.1.1 Comparison

It seems that in the beginning (3.5 m/s), Rigid rotor has the slowest rotational speed of 170 RPM while Flexible has the fastest rotational speed of 193 RPM. Semi-Flexible whereas has the average speed that is around 180 RPM.

At 4 m/s, Semi-Flexible and Flexible rotor seems to be rotating at around similar speed with Semi-Flexible rotor leading by only 8 RPM. The Rigid rotor however seems to be the slowest with the rotational speed of around 220 RPM.

At 5 m/s, Rigid rotor increased the rotational speed significantly getting almost close to the Flexible and Semi- flexible rotor whereas Flexible and Semi-flexible rotor speed was same. The rotational speed of the Rigid Rotor was 330 RPM, while Flexible Rotor and Semi-Flexible rotor was 350 RPM.

However, things started changing drastically after increasing the speed from 5 m/s. Once the speed increased from 5 m/s, the Semi-Flexible rotor and Rigid rotor started taking the lead significantly while Flexible rotor started slowing down. The rotational speed of Semi-Flexible rotor was 461 RPM, while the rotational speed of the Rigid Rotor and Flexible rotor was 433 RPM and 430 RPM respectively.

The figure 17 portrayed below shows the rotational speed in revolution per minute (RPM) and velocity of the wind tunnel in metre per second (m/s). From the graph below, we can figure out the difference in rotational speed and velocity in different speeds.

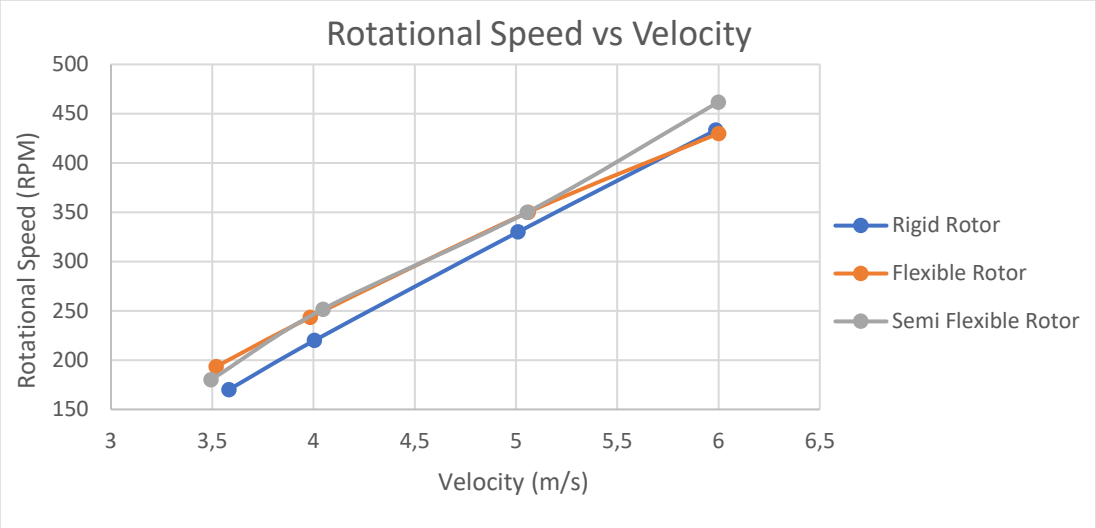

Fig 17: Graph of Rotational Speed vs Velocity

As the tip speed ratio is directly proportional to the rotational speed of the rotor, radius of the rotor and is inversely proportional to the speed of the wind, we can predict the results of tip speed ratio from the rotational speed of the turbine too above.

The higher the rotational speed, the higher the tip speed ratio can be. For the rigid rotor at 3.5 m/s, the tip speed ratio is slowest that is 0.29. While, at the same speed, the tip speed ratio for the Flexible and Semi-Flexible rotor is 0.33 and 0.31 respectively. The difference in tip speed ratio is huge between Rigid rotor and any of the other two rotors.

At 4 m/s, Rigid rotor has the tip speed ratio of 0.331 m/s, while flexible rotor has 0.368 m/s. Semi-flexible rotor has the highest tip speed ratio with 0.37.

At 5 m/s, Rigid rotor has a tip speed ratio of 0.3966, Semi -flexible and Flexible rotor has a value of 0.42 and 0.4165 respectively. Both Flexible and Semi-flexible rotor seems to have similar performance when the wind speed is around 5 m/s.

Whereas, at 6 m/s things starts to shift drastically. While the rigid rotor starts behaving better at higher speeds, flexible rotor seems to go down slowly. At 6 m/s, rigid rotor has the value of 0.44 while flexible rotor has a value of 0.43. The Semi-flexible rotor, however, has the tip speed ratio of 0.463. The difference between the Semi- flexible and Flexible rotor is 0.03. The rigid rotor starts leading the Flexible rotor at this speed.

The figure 18 portrayed below shows the Tip Speed Ratio and velocity when we plot it together in different wind speeds. It is a subtle format for data visualization.

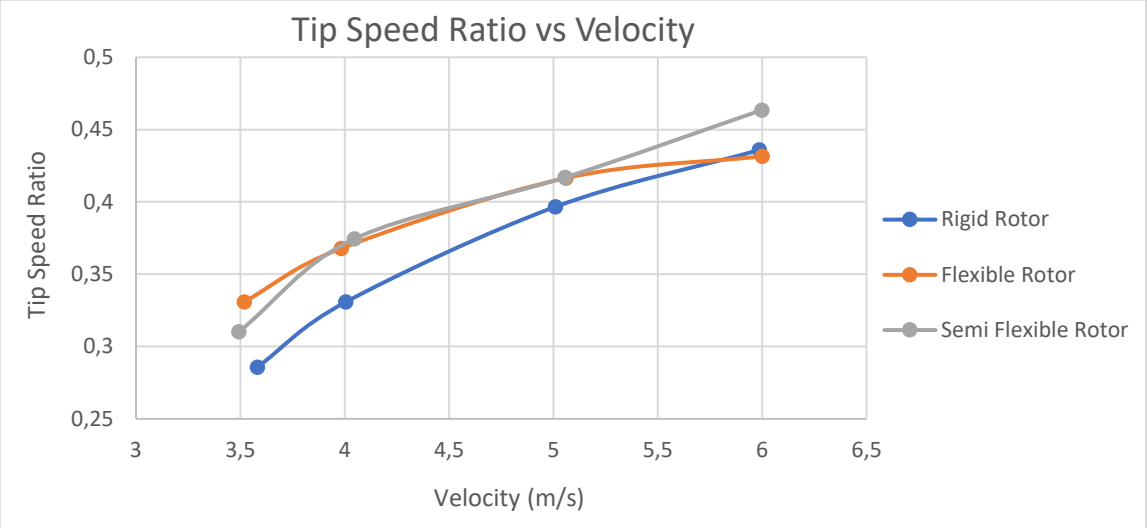

Fig 18: Graph of Tip Speed Ratio vs Velocity

As the average Reynolds number (Re) is greater than 4000 that is Re > 4000, we can say that the air flow is turbulent. We can also predict that the airflow is chaotic, unpredictable and mixes significantly. When the speed is 3.5 m/s. the rigid rotor has the highest Re value with 46289 while Semi–flexible rotor has the lowest Re with 44928. Shear stress is negligible for the higher Reynolds number as inertial forces dominate the viscous force. At 4 m/s, Semi-Flexible rotor has the highest Re with 52045 while at 6 m/s, Flexible rotor has the highest RE of 65157. However, at 6 m/s, all the rotor seems to have similar Reynolds number leading by Rigid rotor followed by Flexible and Semi-Flexible rotor simultaneously.

The figure 19 below portrays the visualization of the relationship between Reynolds Number and velocity.

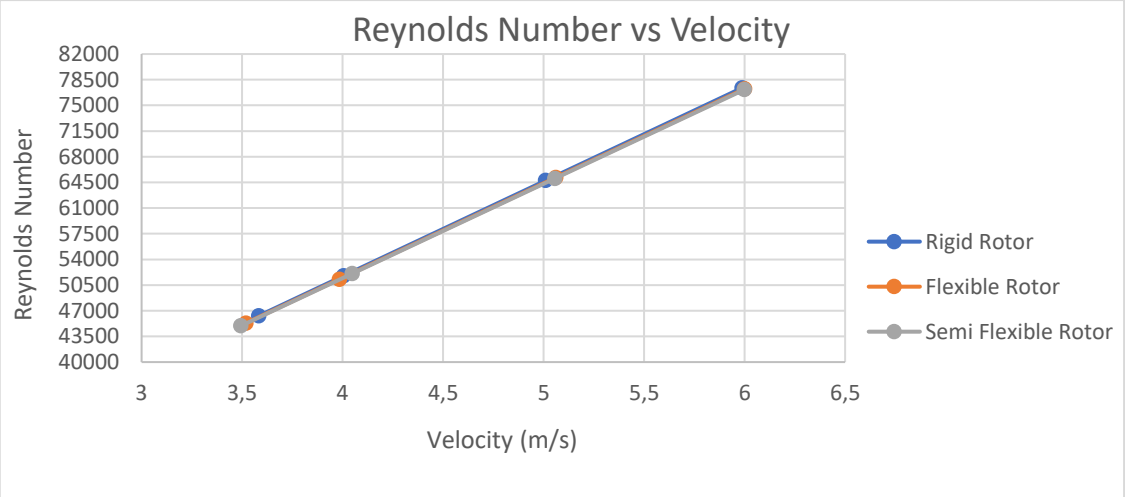

Fig 19: Graph of Reynolds Number vs Velocity

The data above in the picture is the simplified version of the measurements above with only the average numbers at relevant velocities. This makes it easier to understand and see the clearer picture of the calculations done.

Table 13: Average values of all the calculations done above.

Rigid Rotor					
	Velocity(m/s)	Rotational Speed (RPM)	Rotational Speed (rad/s)	Tip Speed Ratio (TSR)	Reynolds Number (Re)
Average at (3.5 m/s)	3.58	170.00	17.80	0.29	46289
Average at (4.0 m/s)	4.00	220.00	23.04	0.33	51760
Average at (5.0 m/s)	5.01	330.00	34.56	0.39	64748
Average at (6.0 m/s)	5.99	433.33	45.38	0.44	77371
Flexible Rotor					
Average at (3.5 m/s)	3.52	193.33	20.25	0.33	45305
Average at (4.0 m/s)	3.98	243.33	25.48	0.37	51293
Average at (5.0 m/s)	5.06	350.00	36.65	0.42	65157
Average at (6.0 m/s)	6.00	430.00	45.02	0.43	77261
Semi Flexible Rotor					
Average at (3.5 m/s)	3.49	180.00	18.85	0,31	44928
Average at (4.0 m/s)	4.05	251.67	26.35	0.37	52045
Average at (5.0 m/s)	5.05	350.00	36.50	0.45	65013
Average at (6.0 m/s)	5.99	461.67	48.35	0.46	77145

The data in the Table 13 above is the simplified version of the measurements above with only the average numbers at relevant velocities. This makes it easier to understand and see the clearer picture of the calculations done.

In a nutshell, from studying and analysing the measurements, we can conclude that Flexible rotor has interestingly good performance at the lower speeds while at higher speed Semi-Flexible rotor gives the better performance. There can be many reasons for this: the first one being the airflow from the wind tunnel around the rotor blades. The other reasons could be the increased drag, transition to turbulence, noise and vibration, aerodynamics, flexibility, weight, and material properties. The results show the possibility that the use of flexible materials could be beneficial in contribution towards the development and advancement of the VAWTs only if we are able to find the material that can withstand wind pressure, different kinds of weather conditions, durability and strength, fatigue resistance , manufacturability, recyclability, dynamic response and cost-effectiveness as selecting the wind turbine blades is a complex process which involves trade-offs among various factors.

4.2 Statistical Difference Calculation

The concept of statistical disparity, commonly referred to as statistical significance, is employed within the field of statistics to assess whether variances or trends in data are more likely attributable to random variations or coincidence, or if they genuinely signify an effect or connection. To put it differently, this concept helps us ascertain whether an observed distinction between sets of data or variables holds significance, rather than being a consequence of random variations. During data analysis, researchers often engage in group or variable comparisons to evaluate hypotheses or draw inferences. It plays a vital role in wind tunnel testing by helping us measure how differently the data points are from each other. This is crucial for checking the accuracy of tests that study how things move through the air. It allows us to confirm how accurate our measurement tools are and whether the changes we make in the test impacts or not. Calculating and analysing Statistical Difference gives us a precise and number-based way to understand things, making our tests more trustworthy, aiding smarter decisions in design, and contribute to advancements in the fields like aerospace and automotive engineering industries.

As we measured the data (velocity and rotational speed) two times in two different days (27^{th} and 28^{th} June 2023), the data turned out to be somehow different both times. Even though the measurements were very close to each other, we calculated the standard deviation to understand how much the data were scattered.

Table 14: Statistical Difference between measurements at two different dates for Rigid and Flexible rotor

Rigid Rotor				Semi-Flexible Rotor			
28th June, 2023	Estimated average Velocity:	Standard Deviation at Velocities	Standard Deviation at Rotational Speeds	28th June, 2023	Estimated average Velocity:	Standard Deviation at Velocities	Standard Deviation at Rotational Speeds
	3.5 m/s	0.02	0.00		3.5 m/s	0.03	0.00
	4.0 m/s	0.01	0.00		4.0 m/s	0.04	4.08
	5.0 m/s	0.02	0.00		5.0 m/s	0.02	0.00
	6.0 m/s	0.03	5.16		6.0 m/s	0.02	4.08
27th June, 2023				27th June, 2023			
	3.5 m/s	0.07	7.52		3.5 m/s	0.04	5.48
	4.0 m/s	0.01	0.00		4.0 m/s	0.04	4.08
	5.0 m/s	0.04	0.00		5.0 m/s	0.02	0.00
	6.0 m/s	0.03	5.16		6.0 m/s	0.02	5.16

Table 15: Statistical Difference between measurements at two different dates for Flexible Rotor

Flexible Rotor			
28th June, 2023	Estimated Velocity:	Standard Deviation at Velocities	Standard Deviation at Rotational Speeds
	3.5 m/s	0.02	5.16
	4.0 m/s	0.03	5.16
	5.0 m/s	0.02	0.00
	6.0 m/s	0.03	0.00
27th June, 2023			
	3.5 m/s	0.04	5.16
	4.0 m/s	0.05	0.00
	5.0 m/s	0.043	5.16
	6.0 m/s	0.05	5.48

4.2.1 Different Rotor Comparison for Statistical difference

For Rigid Rotor, the data perceived on June 28th, at 3.5 m/s, the standard deviation of the velocity was 0.02 and the standard deviation of rotational speed was zero (0). At the same speed, the data measured on 27th June shows the standard deviation of 0.073 for velocity while 7.57 for the rotational speed.

At 4 m/s, the standard deviation for the velocity and rotational speed was 0.005 and 0 respectively measured on 28th June, while it was 0.01 and 0 respectively for the data measured on 27th June.

Likewise, at 5 m/s, the standard deviation for the velocity and rotational speed was 0.01 and zero (0) respectively measured on 28th June, while it was 0.04 and zero (0) respectively for the measurement conducted on June 27th.

For 6 m/s, the standard deviation shows that the data were evenly scattered for the rotational speed in both days. The standard deviation for the velocity and rotational speed on day 28th was 0.03 and 5.16 while on day 27th was 0.031 and 5.16 respectively.

For Semi-Flexible rotor, the data for semi flexible rotor shows that the standard deviation for the velocity and rotational speed at 3.5 m/s on June 28th was 0.03 and zero (0). While on the previous day, it was 0.04 and 5.48 respectively. Likewise, at 4 m/s, the standard deviation was 0.04 and 4.08 for velocity and rotational speed respectively on 28th June. On 27th June, the standard deviation for velocity and rotational speed was 0.04 and 4.08 respectively.

At 5 m/s, for 28th June and 27th June, the data shows 0.01 and 0.02 scatter in the velocity while there was no scatter in rotational speed.

At 6 m/s, the standard deviation for velocity and rotational speed was 0.01 and 4.08 respectively while for the 27th, it was 0.2 and 5.16 respectively.

For Flexible rotor, the standard deviation for the velocity and rotational speed at 3.5 m/s (On 28th June) was 0.01 and zero (0) respectively. While, on 27th June, it was 0.04 and 5.16 respectively for the measurements taken on 28th June.

For 4 m/s, the standard deviation was 0.03 (velocity) and 5.16 (rotational speed) taken on June 28th. At the same speed, the standard deviation of velocity and rotational speed was 0.04 and zero (0) for the measurements taken on June 27th.

Likewise, at 5 m/s, the standard deviation for the velocity and rotational speed was 0.02 and zero (0) respectively measured on 28th June, while it was 0.04 and 5.16 respectively for the measurement conducted on June 27th.

For 6 m/s, the standard deviation for the velocity and rotational speed on day 28th was 0.03 and zero (0) while on day 27th was 0.05 and 5.5 respectively.

4.2.2 Why Statistical Difference?

The statistical difference is significantly small between the two different datasets, so we can conclude that the variance or the dispersion in the results are minute. Therefore, our results are at acceptable range of uncertainty, valid and genuine. The small difference in the measurement could be due to the inherent uncertainties due to factors such as calibration, sensitivity, and noise, experimental conditions despite efforts to replicate the same conditions, even the slight variations in environmental factors could affect the turbines performances), turbulence and flow variations, experimental setup (even small change in the setup such as alignment of the turbine or position of sensors, could lead to variations in measured values), or inherent random fluctuations in the systems.

5 Analysis and Discussion

5.1 Deformation

Phantom Miro M310 12-28 VDC, a high-speed digital camera specially designed for capturing fast-paced objects was used to analyse the behaviour and deformation (if any) of the wind turbine. This camera was used for the precise and detailed motion analysis. As the camera is capable of recording extremely high frame rates and resolutions, it captures even the most rapid motions in fine detail. It captured 3,200 frame rates per second (fps) at its maximum resolution of 1280*800 pixels. It had a flexible exposure control option, including adjustable shutter speeds and precise timing control allowing users to capture images with

optimal exposure settings. Additional Light Emitting Diode (LED) were used to get better lighting inside the wind tunnel.

When the recorded videos were observed and analysed closely, it turned out that the Flexible rotor deformed the most from both edges under the very high-speed conditions. While, at slow wind speeds, all the rotors behaved similar in physical basics as not much difference were observed when analysing it through the camera. It also seems that the Semi-Flexible rotors too tried to deform from the edges, but the edge supports held it strong.

Fig 20: Rigid Rotor at 5 m/s

Fig 21: Rigid Rotor at 6 m/s

Even at fast-paced wind velocity, rigid rotor was strong didn't show any kinds of deformation or physical changes. The vibration produced by this rotor at high-speed velocity was significantly larger than compared to any other rotor.

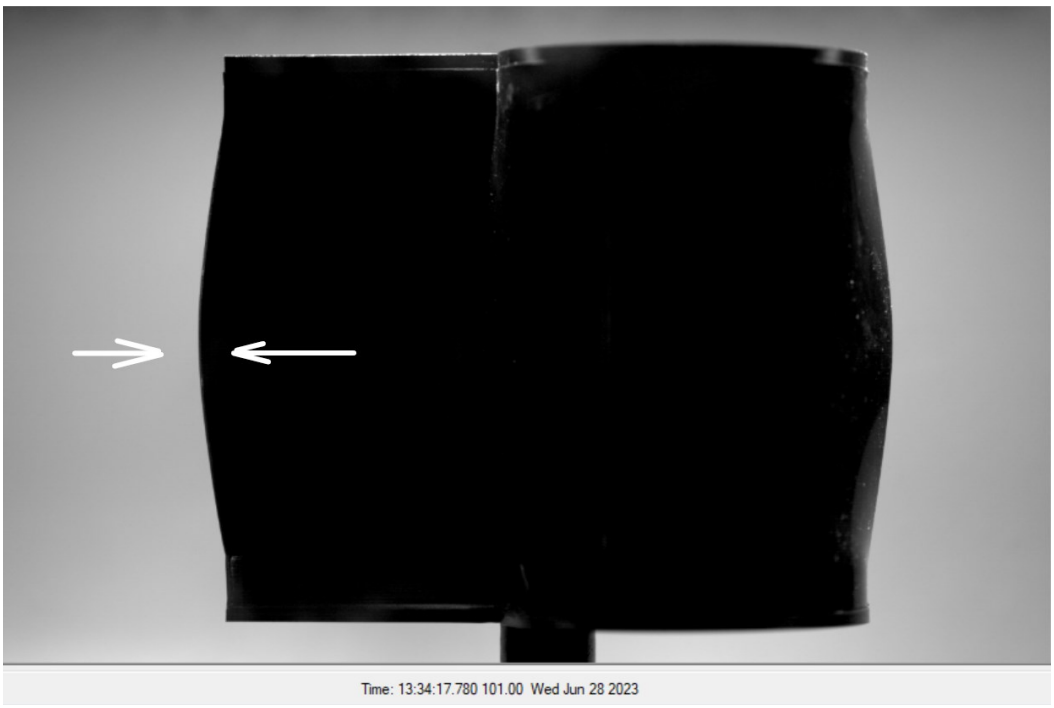

Fig 22: Flexible rotor deformation at 5 m/s

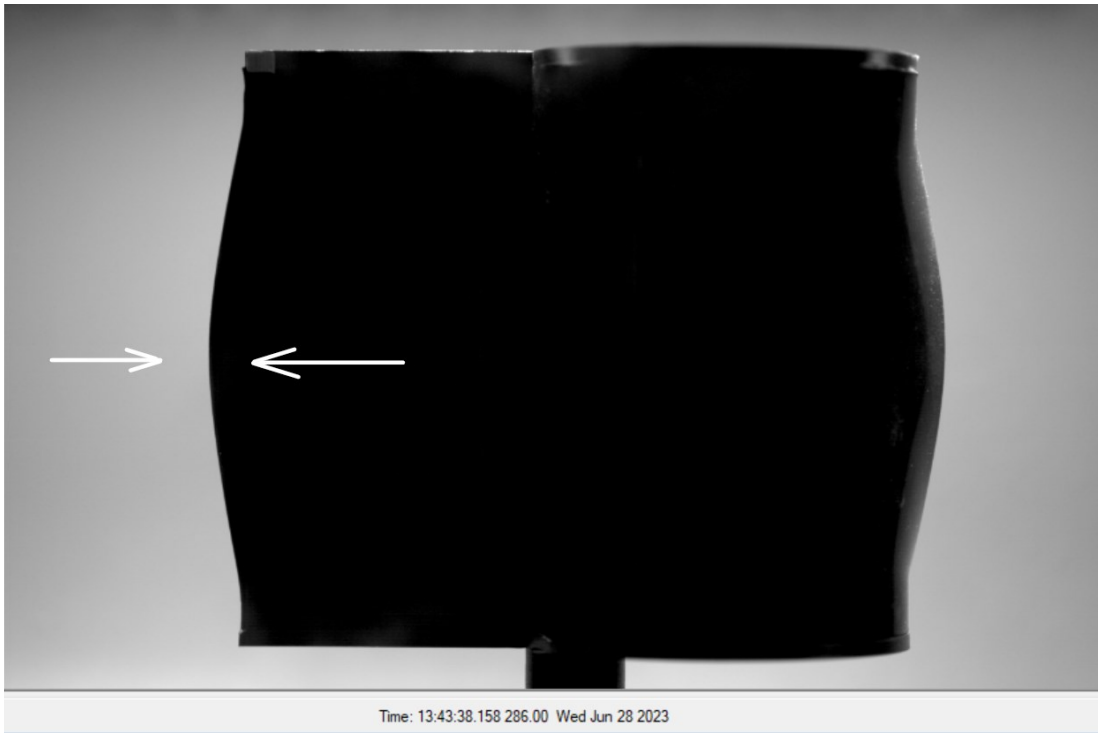

Fig 23: Flexible rotor deformation at 6 m/s

In case of Flexible rotor, the highest deformation around the edges of the rotor blades was observed. This is the prime reason that led this rotor blade reduce its rotational speed at the higher wind speeds. The vibration was not as high as Rigid rotor in this case but flapping sound between air and the flexible rotor on the edges were heard.

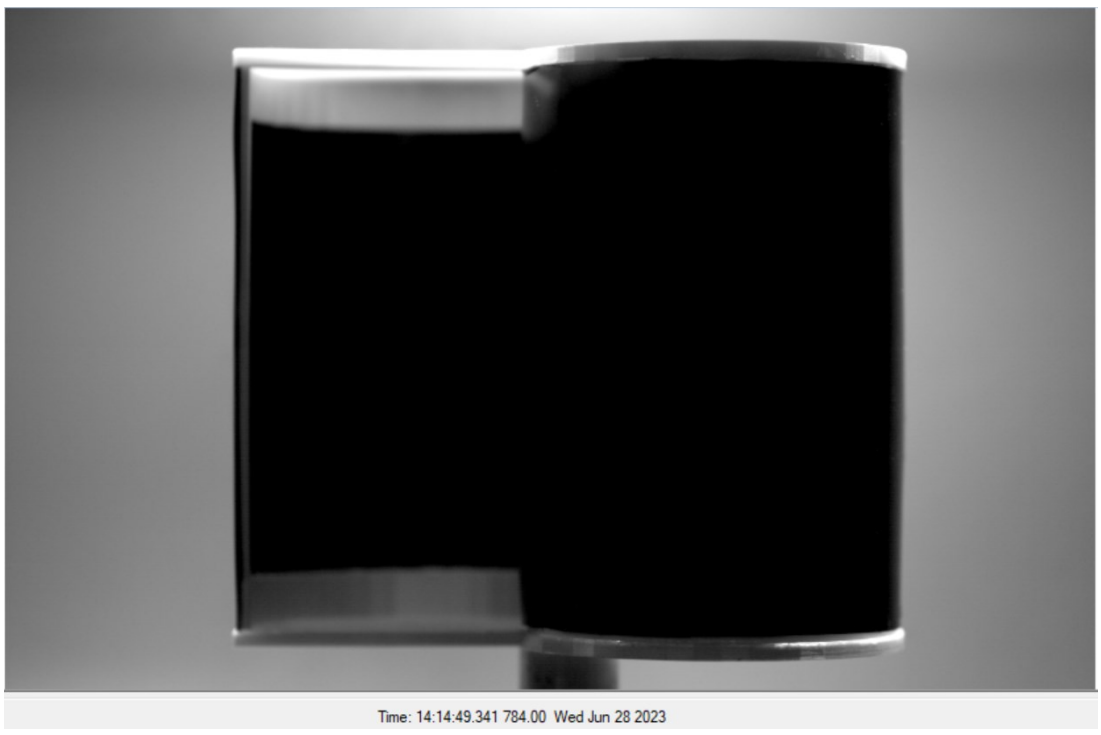

Fig 24: Semi-Flexible rotor at 5 m/s

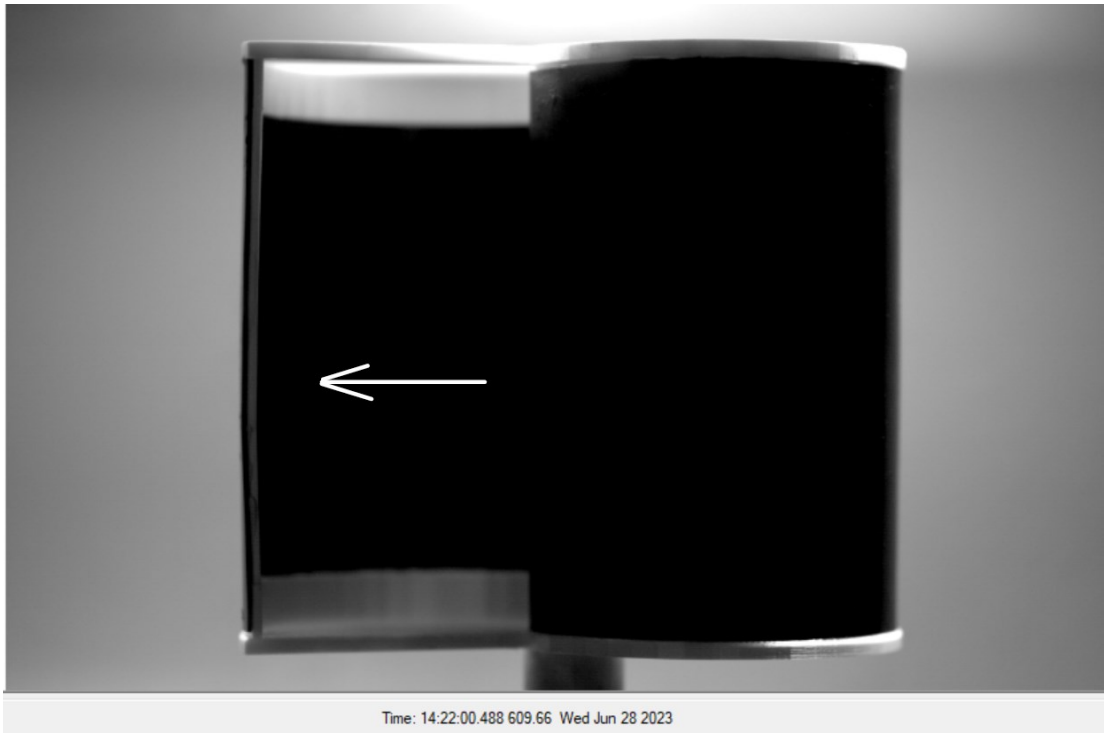

Fig 25: Semi-Flexible Rotor at 6 m/s

While for the Semi-Flexible rotor, a way better performance was observed at higher wind speeds. The only difference between the Semi-Flexible and Flexible rotor was edge support. From the above pictures we can observe that the wind is pushing the walls of the rotor blades, but edge support is holding the material so strong that almost no deformation is seen. So, the Semi-Flexible rotor behaves better also in high-speed conditions.

5.2 Aerodynamic forces on Deformation

The pressure and force exerted by the wind on the rotating blades is defined as aerodynamic forces. Savonius rotors operates on the drag-based principle rather than lift force. When the wind flows over the rotor blades, a low region of low pressure on the leeward side is created and high pressure on the windward side. The difference in this pressure generates a drag force which results in rotation of the blades in rotational manner. As these kinds of turbines can self-start and operate on the low wind speeds, drag-based design increases the efficiency of the turbine to capture the wind energy from every direction extirpating the complex tracking systems.

As these kinds of turbines are drag-based, they produce fluctuating torques which leads to the comparatively lower efficiency and uneven rotational speeds than that of lift-based wind turbines. The drag force acts parallel to the wind direction and opposes the motion of the blades.

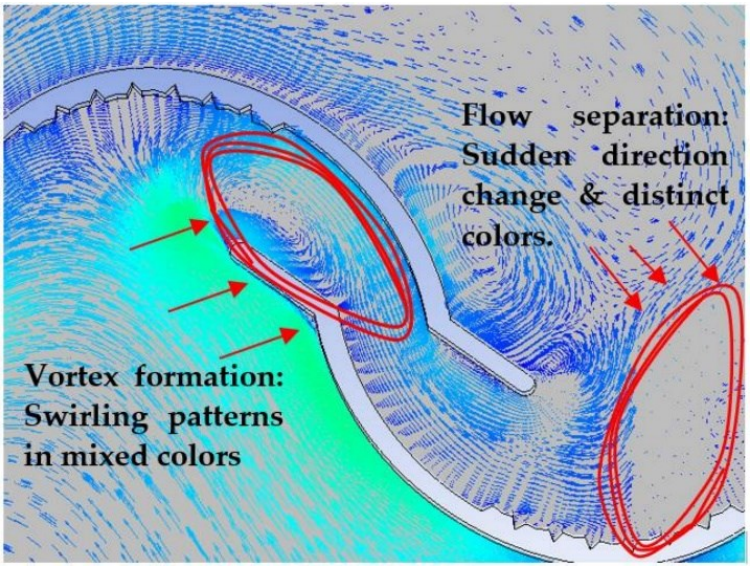

Fig 26: Wind behaviour around the rotor blades (Mu et al., 2022)

There are many reasons for the deformation of the rotor blades while the major reason being the effect of drag force. The flapping force due to the aerodynamic imbalance across the blade span also could be another reason for the deformation. The vibrations and resonance in the higher wind speed is from dynamic loading effects which can potentially amplify aerodynamic forces and lead to the fatigue because of the uneven forces. As the material we used was unconventional, not strong enough and was not designed to handle such forces, it must have led to the deformation under the high load winds.

The above picture represents the complex flow patterns around the rotor blades. It is specifically illustrating the vortex formation and separation of the flow areas. Vortex patterns emerge when flow direction abruptly shifts, leading to fluid twisting and circular motion. Such vortices can affect blade torque and potentially influence the overall efficiency of the Savonius wind turbine (Mu et al., 2022). As we have flexible and unconventional material as our rotor blade, it is likely that the Flexible one could not withstand the sudden fluctuation in vortex formation because of the high pressure towards the separation direction.

5.1 Wind Tunnel effect.

The behaviour of the airflow as it encounters with the rotor blades of the wind turbines within the narrow space of a wind tunnel during testing or analysis is known as Wind Tunnel effect. This effect also has a significant impact on the accuracy of the measurements. The complex airflow patterns can be created due to the interaction between the wind turbine and the wall of the tunnel. This effect can potentially affect the performance characteristics, such as rotational speed, wind velocity and aerodynamic behaviours as well. The proximity of the turbine to the tunnel walls may also impact the flow, leading to the changes in the pressure distribution and vortex shedding because of the slowest moving air adjacent to the wind tunnel walls.

The blockage effects due to the wind tunnel's solid surfaces too can alter the overall aerodynamics and flow patterns of the wind turbine. The size and scale of both wind tunnel and wind turbine can impact the Reynolds number which characterizes the flow regime. The Reynolds number calculated with reference to the wind tunnel can be usually different than the calculation done from the actual working conditions. The corrections and adjustments might be necessary to extrapolate the accurate performance measurements after the consideration of these effects.

In a nutshell, the Semi-Flexible wind turbine performs better at high speed because of the light weight compared to the rigid rotors, aerodynamics as it is more conductive to efficient aerodynamic performances because the design of the rotor blade promoted smoother airflow over the blade, reducing drag and allowing the blade to rotate more freely with comparatively less resistance, flexibility compared to the rigid rotor. Also, better balance and a lower centre of mass could have been another reason contributing to the more stable rotation, reduced vibration, resulting higher rotational speeds. And could be the lower friction coefficient compared to the Rigid rotor which led to lesser energy loss due to friction during rotation.

It is, however, essential to acknowledge the long-term durability and wear resistance of the material used, as it might not be feasible in harsh weather conditions or with prolonged use.

6 Conclusion

The comparison between three different rotors were presented from different analysis with the aim to understand the behaviour of unconventional materials as a rotor blade for Savonius wind turbine. Rotational speed, Tip Speed Ratio and Reynolds Number at specific wind velocity were the prime factors distinguishing the performance differences among each other. At an initial wind speed of 3.5 m/s, the rotor types exhibited varying rotational speeds. The Rigid rotor had the slowest speed, while the Flexible rotor showed the highest speed. This suggests that the Flexible rotor design is more responsive to lower wind speeds, capitalizing on even modest wind resources for efficient rotation. The Semi-Flexible rotor consistently maintained an intermediate rotational speed throughout the wind speed range. This stability in performance indicates that the Semi-Flexible design offers a balanced response to varying wind conditions, making it a reliable option across different wind speeds. As the wind speed increased from 4 m/s to 5 m/s, the Rigid rotor showed a significant speed improvement, indicating its ability to efficiently harness higher wind energy. In contrast, the Flexible and Semi-Flexible rotors exhibited comparable speeds, suggesting that their designs might be optimized for moderately higher wind conditions. Notably, beyond 5 m/s, the Semi-Flexible and Rigid rotors emerged as front-runners, showcasing a substantial increase in rotational speeds. This acceleration indicates that the designs of these rotors effectively adapt to stronger wind regimes, potentially indicating superior aerodynamic characteristics. This phenomenon suggests that the Flexible design might have limitations in maintaining optimal performance under very high wind conditions, potentially due to factors like blade deflection or aerodynamic inefficiencies.

In conclusion, the study of rotor performance at different wind speeds reveals intricate dynamics between rigidity, flexibility, and adaptability. The Rigid rotor emerges as a balanced option, maintaining consistent performance, while the Semi-Flexible rotor showcases remarkable speed improvements at higher wind speeds. The Flexible rotor, though effective at low speeds, faces challenges at extreme wind conditions. These findings provide valuable insights for rotor design optimization and contribute to the advancement of wind energy technology.

Based on the observation, my recommendation and further research could be focused on to investigate the aerodynamic characteristics and structural behaviour of each rotor type in detail. The comprehensive analysis also involving multiple variables such as blade pitch, turbulence intensity, and wind direction would reflect light on the mechanisms behind their performance variation and would be a good reference for the design optimization. Additionally, exploring the interplay between rotor flexibility and aeroelastic effects with innovative design modifications or combining the strength of different rotor might lead to optimized overall performances.

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