

Design, FEA Simulation, and Performance Evaluation of 3-Blade and 4-Blade Vertical Axis Wind Turbines in Low-Speed Urban Wind Conditions

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Abstract -This study presents the design and comparative analysis of 3-blade and 4-blade helical Vertical Axis Wind Turbines (VAWTs) for small-scale urban wind energy applications. The turbines, with a rotor height of 1.5 m and diameter of 1.0 m, were modelled in SolidWorks and analysed using ANSYS Fluent and ANSYS Workbench.

CFD analysis was conducted at wind speeds of 3–6 m/s to evaluate aerodynamic performance. The 4-blade VAWT achieved a higher maximum power coefficient ($C_p = 0.37$) than the 3-blade model ($C_p = 0.32$). Structural analysis showed maximum equivalent stresses of 107.7 MPa and 93.3 MPa for the 3-blade and 4-blade configurations, respectively, with Factors of Safety above 2.6 and 3.0. Modal analysis showed natural frequencies of 18.4–69.2 Hz for the 3-blade model and 21.6–76.9 Hz for the 4-blade model, well above the operating frequency of approximately 3.97 Hz, indicating minimal resonance risk.

Overall, the 4-blade helical VAWT demonstrated better aerodynamic efficiency, lower structural stress and deformation, and improved dynamic stability. The results indicate that the 4-blade configuration is more suitable for compact, low-speed urban wind energy applications.

Index Terms— Vertical Axis Wind Turbine (VAWT), Helical VAWT, Computational Fluid Dynamics (CFD), ANSYS Fluent, Structural Analysis, Modal Analysis, Renewable Energy, Urban Wind Energy, Low-Speed Wind, Power Coefficient.

INTRODUCTION

The increasing demand for clean and sustainable energy has increased interest in small-scale renewable energy systems for urban applications. Conventional Horizontal Axis Wind Turbines (HAWTs) perform efficiently under steady wind conditions but are less suitable for urban environments due to low wind speeds, turbulence, frequent changes in wind direction, and limited installation space. Vertical Axis Wind Turbines (VAWTs) offer an alternative because of their omnidirectional operation, compact design, lower installation requirements, and suitability for rooftop applications.

Among VAWTs, helical configurations provide smoother rotational motion, reduced torque fluctuations, and improved stability. However, turbine performance is strongly influenced by blade number, geometry, and operating wind conditions. Therefore, evaluating different blade configurations is important for improving performance in low-speed urban environments.

This study investigates and compares 3-blade and 4-blade helical VAWTs designed using SolidWorks. Computational Fluid Dynamics (CFD) analysis using ANSYS Fluent is employed to evaluate aerodynamic characteristics under low wind speeds, while static structural and modal analyses using ANSYS Workbench are performed to assess mechanical

strength and dynamic stability. The study aims to identify the configuration that provides better aerodynamic efficiency, structural safety, and overall suitability for small-scale urban wind energy generation.

METHODOLOGY

The methodology adopted in this study follows a systematic design and simulation approach for evaluating 3-blade and 4-blade helical Vertical Axis Wind Turbines (VAWTs) under low-speed urban wind conditions. The overall procedure consists of problem identification, literature review, turbine-type selection, design-parameter selection, airfoil selection, CAD modelling, Computational Fluid Dynamics (CFD) analysis, static structural analysis, modal analysis, and comparative performance evaluation.

A. Turbine Configuration and Design

Urban environments generally experience low and turbulent wind conditions due to buildings and other obstructions. Therefore, a helical VAWT configuration was selected because of its ability to accept wind from different directions while providing smoother rotational motion, reduced torque pulsation, lower vibration, and improved self-starting characteristics. Two configurations, namely 3-blade and 4-blade helical VAWTs, were considered to investigate the influence of blade number on aerodynamic and structural performance.

The major geometrical parameters, including rotor height, rotor diameter, blade chord length, blade number, and helical geometry, were selected before modelling. A symmetrical airfoil profile was adopted for the blades to accommodate the continuously changing relative wind direction experienced during VAWT rotation.

B. CAD Modelling

Three-dimensional models of the 3-blade and 4-blade VAWTs were developed using SolidWorks. The modelling procedure included the development of the central shaft, helical blade geometry, support arms, generator housing, and base structure. The individual components were assembled to obtain the complete turbine configurations. The developed models were subsequently imported into ANSYS Workbench for numerical analysis.

C. CFD Analysis

The aerodynamic performance of both turbine configurations was investigated using ANSYS Fluent. A computational fluid domain was created around the turbine geometry, followed by the definition of a rotating region surrounding the rotor. Appropriate meshing and boundary conditions were applied to represent the airflow around the turbine.

CFD simulations were conducted at wind speeds of 3, 4, 5, and 6 m/s. The analysis focused on velocity distribution, pressure distribution, turbulence characteristics, wake behaviour, and overall aerodynamic performance. A

pressure-based solver and the $k-\omega$ turbulence model were employed for the numerical simulations. The CFD results were used to compare the flow characteristics and aerodynamic performance of the two turbine configurations.

D. Static Structural Analysis

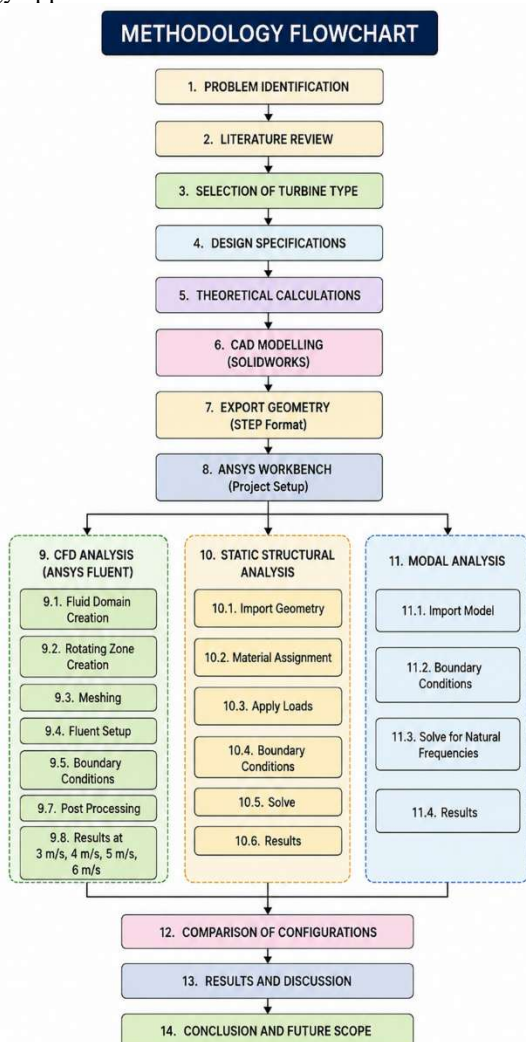
Static structural analysis was performed in ANSYS Workbench to evaluate the mechanical strength of the turbine under aerodynamic loading. Material properties, mesh conditions, supports, and loading conditions were defined for both configurations. The principal structural parameters evaluated were total deformation, equivalent stress, equivalent elastic strain, and factor of safety. These parameters were used to determine whether the turbine structures could safely withstand the considered wind-loading conditions.

E. Modal Analysis

Modal analysis was carried out to investigate the dynamic behaviour and vibration characteristics of the turbines. The natural frequencies and corresponding mode shapes of both the 3-blade and 4-blade configurations were determined. These natural frequencies were compared with the turbine operating frequency to assess the possibility of resonance during normal operation.

F. Comparative Evaluation

Finally, the CFD, structural, and modal analysis results of the two configurations were compared. Aerodynamic parameters such as velocity, pressure, turbulence, and power performance were considered together with structural deformation, stress, factor of safety, and natural frequencies. Based on this integrated comparison, the suitability of the 3-blade and 4-blade helical VAWTs for low-speed urban wind-energy applications was evaluated.



OBJECTIVES

The primary objective of this study is to design and comparatively evaluate 3-blade and 4-blade helical Vertical Axis Wind Turbines (VAWTs) for low-speed urban wind conditions. The specific objectives are:

1. To design and evaluate 3-blade and 4-blade helical Vertical Axis Wind Turbines (VAWTs) for low-speed urban wind conditions using CFD to investigate aerodynamic characteristics such as velocity, pressure, turbulence, wake behaviour, torque generation, and overall aerodynamic efficiency.
2. To evaluate and compare the structural and dynamic performance of both VAWT configurations using static structural and modal analyses by examining stress, deformation, strain, Factor of Safety (FOS), and natural frequencies, and thereby identify the most efficient, mechanically stable, and suitable configuration for residential and small-scale wind-energy generation.

SCOPE

The scope of this study covers the virtual design, simulation, and performance evaluation of the proposed VAWTs. It includes the development of 3-blade and 4-blade turbine geometries, assembly modelling of the rotor, shaft, support structures, and housing components, and consideration of lightweight materials such as aluminium and fibre-reinforced composites.

The aerodynamic investigation includes the creation of computational air domains, mesh generation with refined near-wall regions, and CFD simulations at different wind speeds. Velocity, pressure, vorticity, and wake characteristics are evaluated to understand the aerodynamic behaviour of both configurations. Structural analysis includes the application of CFD-derived wind pressure loads and evaluation of stress, deformation, strain, and FOS. Modal analysis is performed to determine the natural frequencies and assess resonance risk.

Finally, the 3-blade and 4-blade configurations are comparatively evaluated to identify the design most suitable for low-speed residential wind-energy applications. The present work is limited to numerical and simulation-based investigation and does not include physical prototype fabrication, experimental wind testing, or integration of electrical generator hardware.

THEORETICAL CALCULATIONS

Parameter	Symbol	Value
Rotor height	H	1.5 m
Rotor radius	R	0.5 m
Rotor diameter	D	1.0 m
Wind velocity	V	5 m/s
Air density	ρ	1.225 kg/m ³
Dynamic viscosity	μ	1.8 × 10 ⁻⁵ kg/m·s

Swept Area:

$$A = D \times H$$

$$A = 1.0 \times 1.5 = 1.5 \text{ m}^2$$

Helical Blade Length:

$$L = \sqrt{H^2 + (2\pi R)^2}$$

$$L = 3.48 \text{ m}$$

Solidity:

$$\sigma = (N \times C)/(\pi D)$$

$$\text{3-Blade: } \sigma = (3 \times 0.17)/(3.14 \times 1) = 0.162$$

4-Blade: $\sigma = (4 \times 0.13)/(3.14 \times 1) = 0.165$

Power Available in Wind:

$P = \frac{1}{2}\rho AV^3$

$P = 0.5 \times 1.225 \times 1.5 \times 5^3 = 114.8 \text{ W}$

Actual Power Output:

$P_{\text{actual}} = C_p \times P$

$P_{\text{actual}} = 0.25 \times 114.8 = 28.7 \text{ W}$

Tip Speed Ratio:

$\lambda = \omega R/V$

Angular Velocity:

$\omega = \lambda V/R$

$\omega = (2.5 \times 5)/0.5 = 25 \text{ rad/s}$

Rotor Speed:

$\text{RPM} = (\omega \times 60)/(2\pi)$

$\text{RPM} = (25 \times 60)/6.283 = 238 \text{ RPM}$

Torque:

$T = P_{\text{actual}}/\omega$

$T = 28.7/25 = 1.15 \text{ N}\cdot\text{m}$

Reynolds Number:

$\text{Re} = \rho VC/\mu$

3-Blade: $\text{Re} = (1.225 \times 5 \times 0.17)/(1.8 \times 10^{-5}) = 57,847$

4-Blade: $\text{Re} = (1.225 \times 5 \times 0.13)/(1.8 \times 10^{-5}) = 44,236$

MODELLING OF 3-BLADE AND 4-BLADE VERTICAL AXIS WIND TURBINE

The 3-blade and 4-blade helical Vertical Axis Wind Turbine (VAWT) models were developed using SolidWorks to compare their aerodynamic behaviour, starting characteristics, rotational stability, and structural feasibility. The turbine geometry was defined using selected parameters such as rotor height, rotor diameter, blade chord length, shaft diameter, and airfoil profile.

A. Design Specifications

The turbine was designed as a compact small-scale system suitable for low-speed urban wind conditions. The main design parameters are:

Parameter	Value
Rotor height	1.5 m
Rotor radius	0.5 m
Rotor diameter	1.0 m
Swept area	1.5 m ²
Airfoil profile	NACA 0018
Shaft diameter	40 mm
Design wind speed	5 m/s

B. Blade Configurations

Two helical blade arrangements were modelled. The 3-blade configuration uses a chord length of 170 mm, blade spacing of 120°, and a helical twist of 360°. The corresponding 4-blade configuration uses a chord length of 130 mm while maintaining the same rotor dimensions and helical form. The different chord lengths were selected to obtain approximately similar rotor solidity for both configurations.

C. Airfoil Selection

The NACA 0018 symmetrical airfoil was selected for the blade profile. A symmetrical airfoil is suitable for VAWTs

because the blades experience continuously changing relative wind directions during rotation. The NACA 0018 profile was selected because of its symmetrical geometry, good lift-to-drag characteristics, adequate thickness for structural strength, and suitability for low Reynolds number operation. The airfoil coordinates were imported into SolidWorks and scaled according to the required blade chord lengths.

D. CAD Modelling Procedure

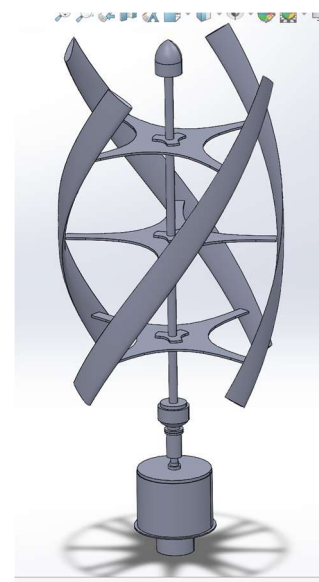
The complete turbine geometry was developed in SolidWorks using the following procedure:

1. The central shaft was created with the specified dimensions.
2. A helical path was generated using the helix feature.
3. NACA 0018 airfoil coordinates were imported and scaled to the required chord length.
4. The airfoil profile was swept along the helical path to generate the twisted blade geometry.
5. Circular patterning was used to produce the 3-blade and 4-blade configurations.
6. Support arms and other assembly components were added to obtain the complete VAWT model.
7. The completed CAD models were exported in STEP format for further analysis in ANSYS.

The developed models provide the geometric basis for subsequent CFD, structural, and modal analyses and enable direct comparison of the two blade configurations under identical operating conditions.



3-Blade Helical VAWT



4-Blade Helical VAWT

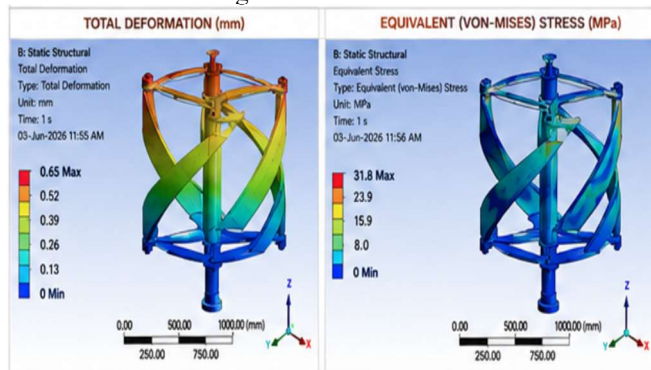
STRUCTURAL, CFD, MODAL ANALYSIS OF 3-BLADE AND 4-BLADE VERTICAL AXIS WIND TURBINE

The aerodynamic, structural, and dynamic performances of the developed 3-blade and 4-blade helical VAWTs were evaluated using ANSYS Workbench. Static Structural Analysis was used to determine mechanical strength under wind loading, Computational Fluid Dynamics (CFD) was used to investigate airflow characteristics, and Modal Analysis was performed to evaluate vibration behaviour and resonance safety.

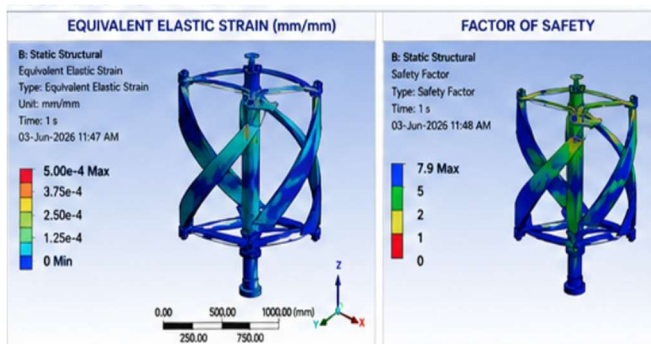
A. Static Structural Analysis

Static Structural Analysis was carried out to evaluate the ability of both turbine configurations to withstand aerodynamic loading. The SolidWorks models were imported into ANSYS Workbench, and Aluminium Alloy was assigned as the structural material. A fixed support was applied at the shaft base, and aerodynamic pressure loads were applied to the turbine structure. The models were meshed and solved for equivalent elastic strain, total deformation, equivalent stress, and Factor of Safety (FOS).

The structural results showed that deformation and stress increased with increasing wind velocity. For the 3-blade VAWT, total deformation increased from 0.18 mm at 3 m/s to 0.75 mm at 6 m/s, while the 4-blade configuration increased from 0.15 mm to 0.65 mm. The corresponding maximum equivalent stresses at 6 m/s were 107.7 MPa and 93.3 MPa, respectively. The minimum FOS values were 2.6 for the 3-blade and 3.0 for the 4-blade configurations, indicating that both designs remained structurally safe under the considered loading conditions.



Total Deformation



Equivalent Elastic strain

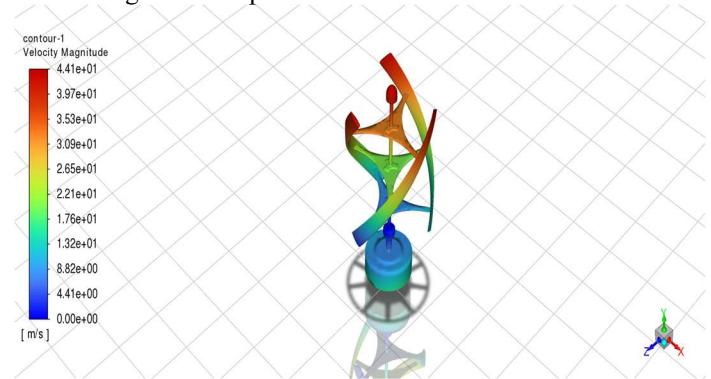
B. Computational Fluid Dynamics Analysis

CFD analysis was performed using ANSYS Fluent to investigate the aerodynamic performance of both VAWT configurations. The CAD geometry was imported into ANSYS Workbench, and a computational fluid domain was created around the turbine. A rotating region was defined

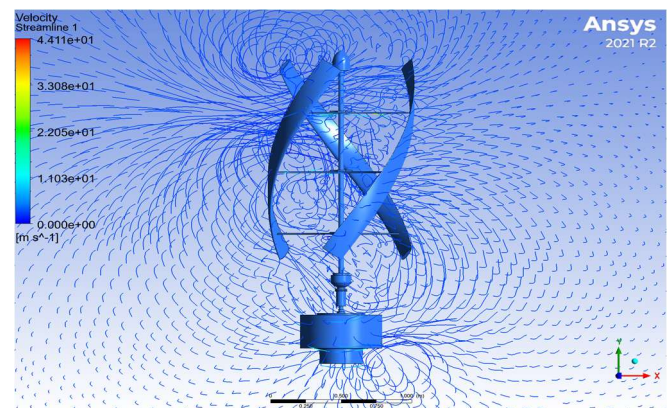
around the rotor, followed by mesh generation with local refinement near the blade surfaces.

The simulations were performed at inlet wind velocities of 3 m/s, 4 m/s, 5 m/s, and 6 m/s. A pressure outlet condition was specified at the downstream boundary, and the SST $k-\omega$ turbulence model was employed to represent turbulent airflow around the blades. The principal CFD outputs included velocity contours, pressure distribution, streamlines, torque generation, turbulence characteristics, and power coefficient.

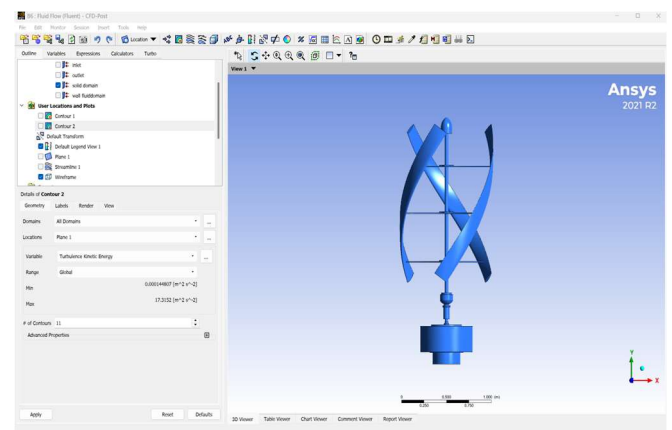
The simulations were used to examine acceleration of airflow around the blade surfaces, pressure variation between the advancing and returning blades, wake formation behind the rotor, and turbulent kinetic energy. The power coefficient was also used to compare the energy extraction capability of the two configurations. CFD simulations were repeated for both turbine models under the selected low-speed wind conditions. The maximum power coefficient obtained was 0.32 for the 3-blade VAWT and 0.37 for the 4-blade VAWT, showing better aerodynamic performance of the 4-blade configuration under the investigated low-speed wind conditions.



Velocity Contour Results



Streamlines



Turbulence

C. Modal Analysis

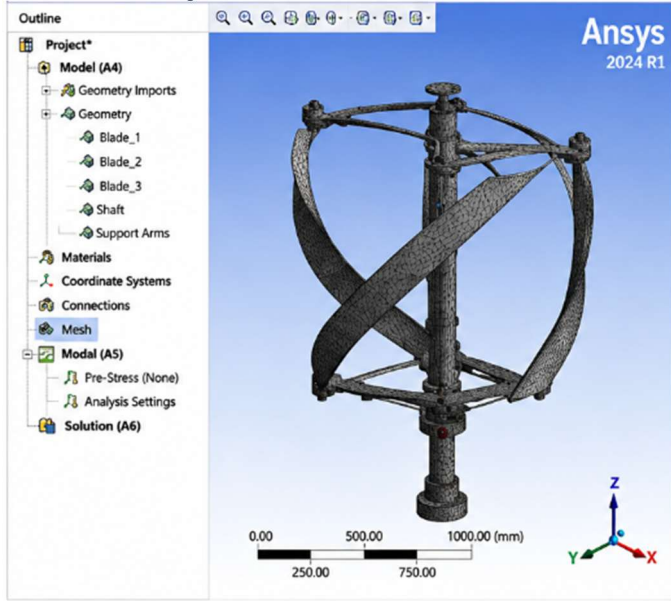
Modal Analysis was performed to determine the natural frequencies and corresponding mode shapes of the two VAWTs. The same turbine geometries and Aluminium Alloy material properties used for structural analysis were adopted. The turbine was fixed at the support location, and the first six vibration modes were calculated using ANSYS Workbench. The free vibration behaviour of the turbine is represented by

[M]{ẍ} + [K]{x} = 0

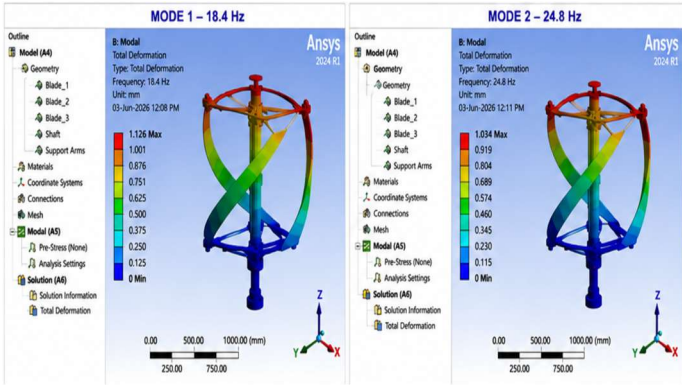
where [M] is the mass matrix, [K] is the stiffness matrix, and {x} is the displacement vector. Modal analysis is important because resonance may occur if the turbine operating frequency approaches one of its natural frequencies, resulting in excessive vibration and possible fatigue damage.

The first six natural frequencies of the 3-blade VAWT ranged from 18.4 Hz to 69.2 Hz, whereas those of the 4-blade VAWT ranged from 21.6 Hz to 76.9 Hz. The operating frequency of the turbine was approximately 3.97 Hz, which is substantially lower than the first natural frequency of either configuration. Therefore, resonance is unlikely during normal operating conditions.

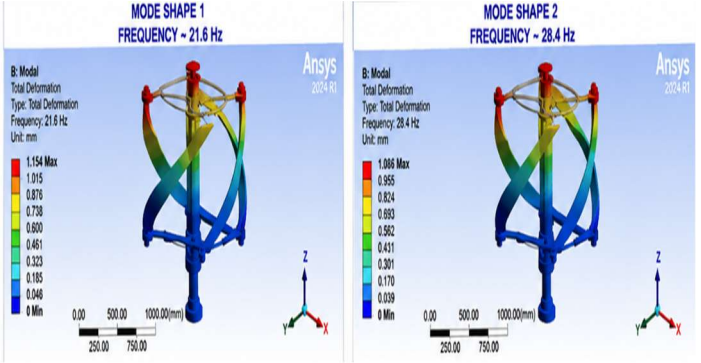
Overall, both turbine configurations satisfied the structural and dynamic safety requirements. However, the 4-blade VAWT exhibited lower structural deformation and stress, higher natural frequencies, a higher Factor of Safety, and a higher power coefficient, indicating improved aerodynamic efficiency, stiffness, and vibration resistance compared with the 3-blade configuration.



Mesh Generation



Mode	Frequency (Hz)
1	18.4
2	24.8
3	31.5
4	42.3
5	55.7
6	69.2



Mode	Frequency (Hz)
1	21.6
2	28.4
3	36.8
4	48.7
5	62.4
6	76.9

Comparative Analysis

Parameter	3-Blade	4-Blade	Better
First Natural Frequency	18.4 Hz	21.6 Hz	4-Blade
Sixth Natural Frequency	69.2 Hz	76.9 Hz	4-Blade
Structural Stiffness	Good	Excellent	4-Blade
Dynamic Stability	Good	Excellent	4-Blade

RESULTS AND DISCUSSION

The performance of the 3-blade and 4-blade helical VAWTs was evaluated based on CFD, static structural, and modal analysis results. The major aerodynamic parameters considered were velocity magnitude, static pressure distribution, and turbulent kinetic energy, while structural performance was assessed using total deformation, equivalent stress, equivalent elastic strain, and Factor of Safety (FOS). Modal analysis was used to compare the natural frequencies and dynamic stability of both configurations.

A. CFD Results

The CFD results showed that airflow accelerated around the blade tips and curved blade surfaces, while a lower-velocity wake region developed downstream of the rotor. For the 3-blade configuration, the maximum local velocity increased from 31.2 m/s at 3 m/s inlet velocity to 44.1 m/s at 4 m/s and 44.11 m/s at 5 m/s. This indicates increased interaction and momentum transfer between the airflow and turbine blades as the inlet wind velocity increases.

The static pressure distribution showed positive pressure on the windward blade surfaces and negative pressure on the opposite surfaces. This pressure difference contributes to aerodynamic torque generation. For the investigated cases, the maximum/minimum pressures were approximately 116/−170 Pa at 3 m/s, 113.75/−171.51 Pa at 4 m/s, and 117/−169 Pa at 5 m/s.

Comparison of the two configurations showed that the 4-blade VAWT produced more uniform velocity contours because of the additional blade and greater wind interception area. The 3-blade model developed higher localized velocity regions due to wider spacing between the blades, which provides greater potential for higher rotational speed. In contrast, the 4-blade configuration maintained smoother airflow around the rotor as wind velocity increased.

The pressure distribution was also more balanced in the 4-blade configuration. The 3-blade VAWT exhibited stronger pressure fluctuations between different blade positions, whereas the 4-blade configuration produced a more stable torque-generating pressure difference. Consequently, the 4-blade design exhibited smoother torque generation and lower torque ripple.

In terms of turbulence, the 3-blade configuration generated stronger wake zones due to the larger spacing between blades. The 4-blade configuration produced more distributed turbulence with lower intensity fluctuations, although localized turbulence increased slightly in regions where blade interactions occurred. The controlled turbulence and smoother wake behaviour of the 4-blade configuration indicate lower aerodynamic losses and improved low-speed performance.

The maximum power coefficient obtained was $C_p = 0.32$ for the 3-blade VAWT and $C_p = 0.37$ for the 4-blade VAWT. Therefore, the 4-blade configuration demonstrated higher aerodynamic efficiency under the investigated low-speed wind conditions.

B. Structural Analysis Results

The structural analysis confirmed that both turbine configurations remained within safe operating limits. As wind speed increased, deformation, stress, and strain increased while the Factor of Safety decreased.

Wind Speed	Configuration	Deformation (mm)	Stress (MPa)	FOS
3 m/s	3-Blade	0.18	58.3	4.8
	4-Blade	0.15	53.8	5.2
4 m/s	3-Blade	0.33	70.0	4.0
	4-Blade	0.28	63.6	4.4
5 m/s	3-Blade	0.52	87.5	3.2
	4-Blade	0.45	77.8	3.6
6 m/s	3-Blade	0.75	107.7	2.6
	4-Blade	0.65	93.3	3.0

The 4-blade turbine consistently exhibited lower deformation and equivalent stress together with a higher FOS. At the maximum investigated wind speed of 6 m/s, the 4-blade configuration showed 0.65 mm deformation and 93.3 MPa stress, compared with 0.75 mm and 107.7 MPa for the 3-blade configuration. Both designs were classified as structurally safe, but the 4-blade configuration demonstrated better structural performance.

C. Modal Analysis Results

The natural frequencies obtained from modal analysis increased with mode number for both configurations. The results are summarized below.

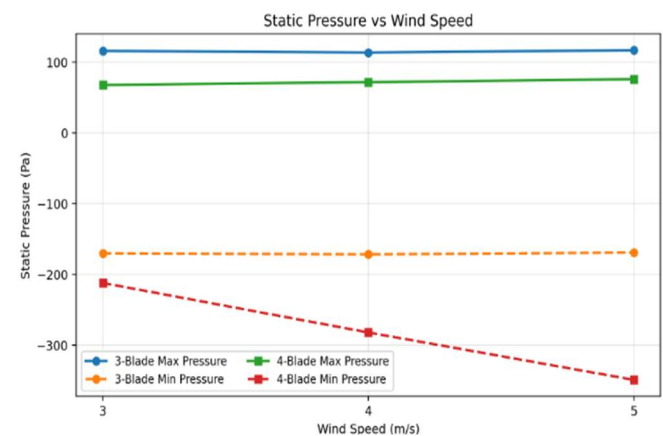
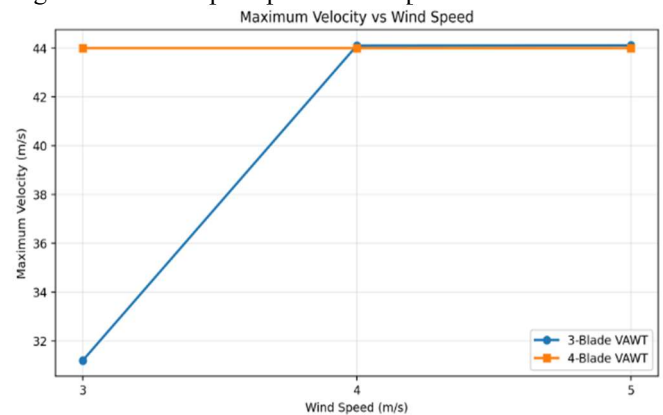
Mode	3-Blade (Hz)	4-Blade (Hz)
1	18.4	21.6
2	24.8	28.4
3	31.5	36.8
4	42.3	48.7
5	55.7	62.4
6	69.2	76.9

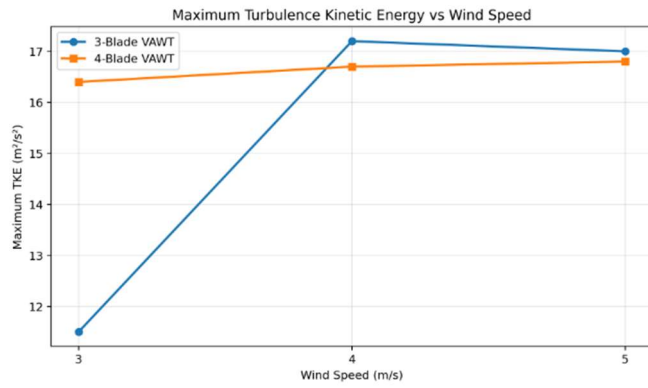
The 4-blade VAWT exhibited higher natural frequencies for all six modes, indicating greater structural stiffness and improved vibration resistance. The first natural frequencies of 18.4 Hz and 21.6 Hz for the 3-blade and 4-blade models, respectively, are considerably higher than the turbine operating frequency of approximately 3.97 Hz. Therefore, resonance is unlikely during normal operation.

D. Overall Comparison

The 4-blade VAWT demonstrated better self-starting capability due to its higher solidity and greater wind interception area. It also exhibited lower torque ripple, smoother power output, better low-wind performance, more uniform pressure distribution, and improved structural and dynamic stability. The 3-blade configuration, however, has lower rotor weight, greater structural simplicity, easier manufacturing, and higher maximum rotational-speed potential.

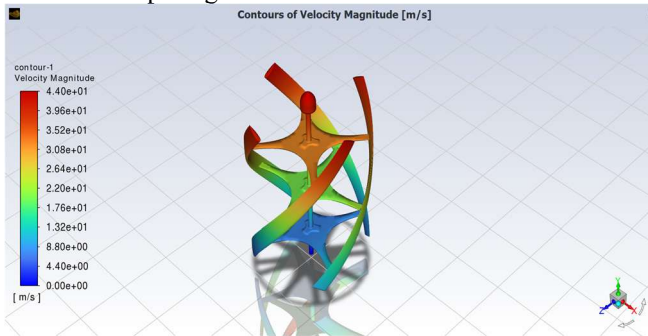
Considering the combined CFD, structural, and modal results, the 4-blade helical VAWT provides the better overall performance for low-speed urban wind applications. Its higher power coefficient, lower deformation and stress, higher FOS, improved self-starting behaviour, and higher natural frequencies make it more suitable where aerodynamic efficiency, structural reliability, and operational stability are the primary requirements. The 3-blade configuration remains advantageous where lower weight, simpler construction, and higher rotational-speed potential are preferred.



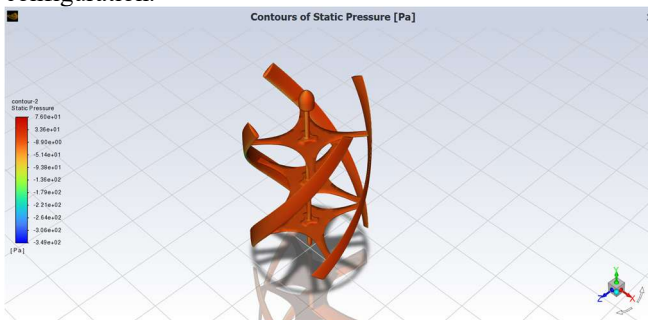


The comparative graphs show the aerodynamic behaviour of the 3-blade and 4-blade VAWTs at wind speeds of 3, 4, and 5 m/s.

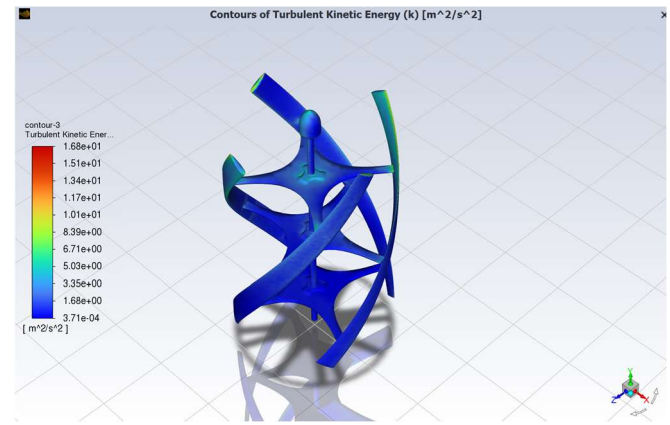
Velocity: The maximum local velocity increases considerably for the 3-blade VAWT from 31.2 m/s at 3 m/s to approximately 44.1 m/s at 4–5 m/s. The 4-blade VAWT maintains maximum local velocities of approximately 44 m/s across the investigated conditions. The report further indicates that the 4-blade configuration provides a more uniform flow distribution, whereas the 3-blade configuration develops stronger localized velocity regions because of its wider blade spacing.



Static Pressure: Both configurations develop positive pressure on the wind-facing blade surfaces and negative pressure on the opposite surfaces, producing the pressure difference required for rotor torque. Although the pressure magnitudes vary with wind speed and blade position, the 4-blade configuration shows more balanced pressure loading across the rotor. This contributes to smoother torque generation and reduced vibration compared with the 3-blade configuration.



Turbulent Kinetic Energy (TKE): TKE generally increases as the interaction between the airflow and rotating blades becomes stronger. The 3-blade results increase from 11.5 m^2/s^2 at 3 m/s to approximately 17 m^2/s^2 at 4–5 m/s. The 4-blade results remain around 16.4–16.8 m^2/s^2 , indicating comparatively controlled turbulence. According to the report, the 3-blade configuration produces stronger wake zones, while the 4-blade configuration distributes turbulence more uniformly with lower intensity fluctuations.



Overall, the graphs indicate that the 4-blade VAWT provides smoother airflow, more balanced pressure distribution, and better-controlled turbulence, supporting its suitability for stable operation under low-speed urban wind conditions.

CONCLUSION AND FUTURE SCOPE

A. Conclusion

This study presented the design, modelling, and comparative analysis of 3-blade and 4-blade helical Vertical Axis Wind Turbines (VAWTs) for low-speed urban wind-energy applications. The turbine models were developed using SolidWorks, while CFD, static structural, and modal analyses were performed using ANSYS Fluent and ANSYS Workbench.

The CFD results showed that both configurations can operate under the investigated low-speed wind conditions. However, the 4-blade VAWT demonstrated better aerodynamic performance, achieving a maximum power coefficient of 0.37, compared with 0.32 for the 3-blade VAWT. The additional blade provided improved wind-energy capture, pressure distribution, torque generation, and operational stability.

Structural analysis confirmed that both designs were within safe operating limits. The 4-blade VAWT exhibited lower maximum deformation and equivalent stress and maintained a higher Factor of Safety than the 3-blade configuration. Modal analysis showed natural-frequency ranges of 18.4–69.2 Hz for the 3-blade VAWT and 21.6–76.9 Hz for the 4-blade VAWT, which are considerably higher than the operating frequency of approximately 3.97 Hz, indicating a low possibility of resonance during normal operation.

Overall, the 4-blade helical VAWT was identified as the better configuration because it provides a favourable combination of aerodynamic efficiency, structural stiffness, vibration resistance, self-starting capability, and operational stability. The 3-blade configuration remains advantageous in terms of lower structural weight, reduced material usage, and higher rotational-speed potential. Therefore, the 4-blade design is considered more suitable for small-scale urban and residential wind-energy applications.

B. Future Scope

Future work can focus on the fabrication and experimental testing of a prototype to validate the numerical results obtained from CFD and structural simulations. Transient CFD simulations incorporating actual rotor motion can also be performed to obtain more realistic predictions of torque and power coefficient.

Further optimization of the airfoil profile, blade chord, and helical twist angle can improve aerodynamic efficiency. Coupled Fluid–Structure Interaction (FSI) and fatigue analyses can be performed to evaluate structural behaviour

under cyclic wind loading, while lightweight composite materials can be investigated to improve the strength-to-weight ratio.

The proposed VAWT can also be integrated with solar photovoltaic systems to develop hybrid renewable-energy systems. Future prototypes may incorporate IoT-based sensors for real-time monitoring of rotational speed, vibration, wind conditions, and power output. Multi-stage or modified helical configurations can also be investigated to further improve turbine performance under low and turbulent urban wind conditions.

REFERENCES

- Alaimo, A., Esposito, A., Messineo, A., Orlando, C., & Tumino, D. (2015). *3D CFD analysis of a vertical axis wind turbine*. *Energies*, 8(4), 3013–3033. <https://doi.org/10.3390/en8043013>
- Armstrong, S., & Tullis, S. (2011). *Power performance of canted blades for a vertical axis wind turbine*. *Journal of Renewable and Sustainable Energy*, 3(1). <https://doi.org/10.1063/1.3549153>
- Bani-Hani, E. H., Sedaghat, A., Al-Shemmary, M., Hussain, A., Alshaieb, A., & Kakoli, H. (2018). *Feasibility of highway energy harvesting using a vertical axis wind turbine*. *Energy Engineering*, 115(2), 61–74. <https://doi.org/10.1080/01998595.2018.11969276>
- Cheng, Q., Liu, X., Ji, H. S., Kim, K. C., & Yang, B. (2017). *Aerodynamic analysis of a helical vertical axis wind turbine*. *Energies*, 10(4), 575. <https://doi.org/10.3390/en10040575>
- Divakaran, U., Ramesh, A., Mohammad, A., & Velamati, R. K. (2021). *Effect of helix angle on the performance of helical vertical axis wind turbine*. *Energies*, 14(2), 393. <https://doi.org/10.3390/en14020393>
- Han, D., Heo, Y. G., Choi, N. J., Nam, S. H., Choi, K. H., & Kim, K. C. (2018). *Design, fabrication, and performance test of a 100-W helical-blade vertical-axis wind turbine at low tip-speed ratio*. *Energies*, 11(6), 1517. <https://doi.org/10.3390/en11061517>
- Hand, B., Kelly, G., & Cashman, A. (2021). *Aerodynamic design and performance parameters of a lift-type vertical axis wind turbine: A comprehensive review*. *Renewable and Sustainable Energy Reviews*, 139, 110699. <https://doi.org/10.1016/j.rser.2020.110699>
- Howell, R., Qin, N., Edwards, J., & Durrani, N. (2010). *Wind tunnel and CFD study of a vertical axis wind turbine*. *Renewable Energy*, 35(2), 412–422.
- Kamoji, M. A., Kedare, S. B., & Prabhu, S. V. (2009). *Performance tests on helical Savonius rotors*. *Renewable Energy*, 34(3), 521–529.
- Karimian, S. M. H., & Abdolahifar, A. (2020). *Performance investigation of a new Darrieus vertical axis wind turbine*. *Energy*, 191, 116551. <https://doi.org/10.1016/j.energy.2019.116551>
- Lampinen, M. J., Kotiaho, V. W., & El Haj Assad, M. (2006). *Application of axial fan theory to horizontal-axis wind turbine*. *International Journal of Energy Research*, 30(13), 1093–1107. <https://doi.org/10.1002/er.1208>
- Lee, Y. T., & Lim, H. C. (2015). *Numerical study of the aerodynamic performance of a 500 W Darrieus-type vertical-axis wind turbine*. *Renewable Energy*, 83, 407–415. <https://doi.org/10.1016/j.renene.2015.04.043>
- Moradi CheshmehBeigi, H., & Geravandi, M. (2023). *Unit commitment risk evaluation considering load uncertainty and wind power*. *Journal of Energy Management and Technology*, 7(3), 134–141. <https://doi.org/10.22109/jemt.2023.311870.1342>
- Paraschivoiu, I. (2002). *Wind Turbine Design: With Emphasis on Darrieus Concept*. Presses Internationales Polytechnique.
- Reza, A., Tolentino, G., & Toledo, M. (2015). *Construction of a helical vertical axis wind turbine for electricity supply*. *Computer-Aided Design and Applications*, 12(Suppl. 1), 9–12. <https://doi.org/10.1080/16864360.2015.1077069>
- Rezaeiha, A., Montazeri, H., & Blocken, B. (2018). *CFD analysis of vertical axis wind turbines: Impact of 2D and 3D simulations on power prediction*. *Energy*, 165, 1120–1135.
- Roy, S., & Saha, U. K. (2015). *Studies on VAWT with varying number of blades*. *Energy Conversion and Management*, 96, 418–428.
- Scheurich, F., Fletcher, T., & Brown, R. (2010, January). *The influence of blade curvature and helical blade twist on the performance of a vertical-axis wind turbine*. In *48th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition* (Paper No. AIAA 2010-1579). <https://doi.org/10.2514/6.2010-1579>
- Sedaghat, A., Assad, M. E. H., & Gaith, M. (2014). *Aerodynamics performance of continuously variable speed horizontal-axis wind turbine with optimal blades*. *Energy*, 77, 752–759. <https://doi.org/10.1016/j.energy.2014.09.048>
- Seralathan, S., Ganesh, C. P. V. S., Venganna, B. P. R., Srinivas, N. S., Chowdary, B. L., Hariram, V., & Premkumar, T. M. (2020). *Simulation studies to analyze the static mechanical properties of helical Savonius vertical-axis wind turbine blade*. *Materials Today: Proceedings*, 33, 3737–3745. <https://doi.org/10.1016/j.matpr.2020.06.139>
- Shah, S., Jain, V., & Ahmed, M. R. (2013). *Study of Savonius rotor performance*. *Renewable and Sustainable Energy Reviews*, 27, 656–664.
- Sharma, M., Rieger, B., Jou, C., & Butka, B. (2012, March). *Development of helical vertical-axis wind turbine*. In *Proceedings of IEEE SoutheastCon 2012* (pp. 1–5). IEEE. <https://doi.org/10.1109/SECon.2012.6196967>
- Takao, M., Takahashi, T., Maeda, T., Kamada, Y., Ogasawara, T., Mizumukai, K., & Takemura, K. (2009). *Power characteristics of a Darrieus rotor with guide vanes*. *Renewable Energy*, 34(4), 713–720.
- Van Bussel, G. J. W., Van Kuik, G. A. M., & Ferreira, C. J. S. (2009). *2D CFD modeling of the VAWT*

- aerodynamics. In *Proceedings of the European Wind Energy Conference* (pp. 1–10). Marseille, France.
25. Wang, Z., Wang, Y., & Zhuang, M. (2018). *Improvement of the aerodynamic performance of vertical-axis wind turbines with leading-edge serrations and helical blades using CFD and Taguchi method*. *Energy Conversion and Management*, 177, 107–121.
<https://doi.org/10.1016/j.enconman.2018.09.028>
26. Wei, N. J., Brownstein, I. D., Cardona, J. L., Howland, M. F., & Dabiri, J. O. (2021). *Near-wake structure of full-scale vertical-axis wind turbines*. *Journal of Fluid Mechanics*, 914, A17.
<https://doi.org/10.1017/jfm.2021.75>