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Integrated CFD and Structural Analysis of Small-Scale Horizontal-Axis Wind Turbine

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ABSTRACT

Introduction: This study conducts a thorough numerical investigation of a small-scale horizontal-axis wind turbine (HAWT) by combining computational fluid dynamics (CFD) with structural finite element analysis (FEA). **Methodology:** The CFD model employs a three-dimensional RANS formulation with an appropriate turbulence closure to capture the detailed flow field around the rotor. The pressure contours and streamline plots revealed blade-induced pressure gradients and the formation of helical tip vortices. The wake velocity deficit and recovery were quantified using velocity slice visualizations downstream of the turbine. The key solver and boundary settings were documented to ensure reproducibility. The structural FEA of the rotor uses load distributions from the CFD to compute the von Mises stress, deformation, and reaction forces at the hub. **Results:** The integrated results provide insights into vortex formation, wake recovery, blade loading, and structural integrity under the operating conditions. The outcomes demonstrated a coherent helical wake, significant tip-vortex strength, stable velocity deficit, and low structural deformation, highlighting the turbine's aerodynamic efficiency and structural robustness for small-scale deployment. These findings are contextualized with the literature on wake prediction and structural response in wind turbines. **Conclusion:** The CFD simulation revealed a well-defined helical wake with strong tip vortices, supported by high-pressure gradient regions on the blade tips and leading edges. The velocity deficit plots showed a pronounced near-wake core and gradual wake recovery, consistent with established research on small-scale turbines. Structural analysis confirmed that the maximum blade tip deflection remained under 3 mm, while the peak von Mises stress (≈ 18.7 MPa) well within the safe limits for materials. Significance: This study yields important insights into both aerodynamic behavior and structural response under operating conditions.

Keywords: *Comprehensive numerical study across disciplines; Finite element analysis for assessing structural integrity; Horizontal-axis wind turbine; Numerical analysis of fluid dynamics; Wind-induced structural loads.*

INTRODUCTION

Wind energy is becoming an increasingly vital component of global electricity generation. The combined capacity of wind power, encompassing both onshore and offshore installations, has now reached several hundred gigawatts, fulfilling a substantial portion of the world's electricity requirements [6]. While the majority of installed turbines are large, multi-megawatt units connected to central grids, there is a rising interest in small-scale horizontal-axis wind turbines (HAWTs) with kilowatt ratings for distributed power generation in both rural and urban settings [6]. These smaller HAWTs offer the potential for localized energy production without the necessity for extensive transmission networks, aligning with sustainable energy objectives and Sustainable Development Goal [6], which emphasizes affordable clean energy access [6].

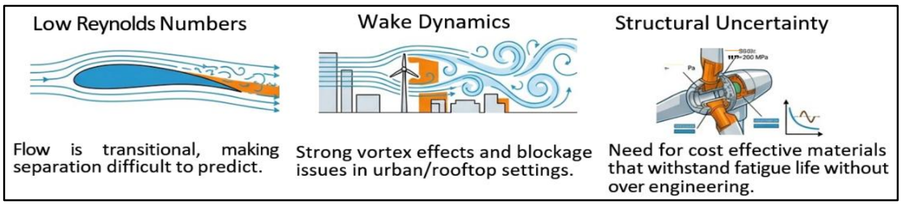

Figure 1. Challenges for small scale HAWT design.

However, these turbines encounter specific challenges, such as aerodynamics at low Reynolds numbers, noise and vibration issues, and maintaining structural integrity under varying loads. These small-scale wind turbines (SWTs) are gaining importance for off-grid, residential, and educational applications due to their cost-effectiveness and adaptability. Nevertheless, accurately predicting their aerodynamic performance and structural behavior remains difficult because of strong wake effects, vortex dynamics, and load-induced deformations. High-fidelity numerical modeling is essential for understanding these phenomena. In this study, a combined CFD and FEA approach was employed to investigate the aerodynamic flow field around a three-bladed SWT and the resulting structural response under operational loading. The CFD model captures pressure gradients and velocity profiles in the near and far wake, while the structural model quantifies deformation and von Mises stress in blades, hub, nacelle, and tower. Notably, the near-wake flow behind a small rotor can exhibit significant velocity deficits and coherent vortices, affecting downstream energy capture and loading. Additionally, blade loads result in internal stresses and deflections that must remain within material limits. This study aims to model the fluid and structural behavior of a representative small HAWT using high-fidelity simulation.

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METHODOLOGY

A comprehensive computational fluid dynamics (CFD) model captures the steady-state wake field at a chosen inlet wind speed, allowing for the analysis of pressure distribution, vortex structures, and wake recovery. These aerodynamic loads are then applied in a structural finite element analysis (FEA) model of the rotor and blades to calculate deformation, von Mises stress, and hub reaction forces. This integrated approach allows for the evaluation of performance and structural safety within the same study. Recent research has highlighted the effectiveness of such integrated CFD-FEA workflows for small wind turbines[3][11]. In this work, we detail the computational domain, meshing strategy, and solver settings, comparing the resulting wake and stress patterns to published results from Scopus-indexed studies. This comparison provides confidence in our findings and places them within the context of small-wind literature.

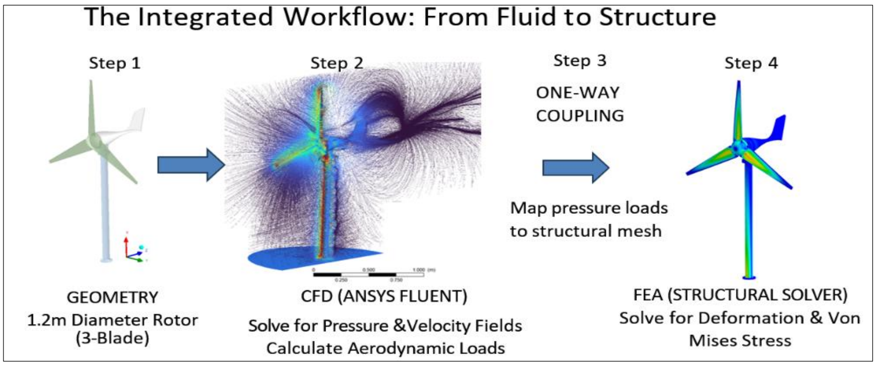

Figure 2. Methodology implemented for the coupled CFD and FEA analysis.

Computational domain and fluid dynamics analysis

The computational domain was designed in three dimensions to simulate a semi-cylindrical wind tunnel surrounding the turbine. The dimensions of this domain were sufficient to allow for the development of the wake. Mesh refinement was specifically applied around the rotor, hub, and wake areas, featuring fine inflation layers on the blade surfaces and tetrahedral elements within the volume. The refinement downstream extended approximately three rotor diameters to effectively capture wake vortices and shear layers.

Geometry and Meshing

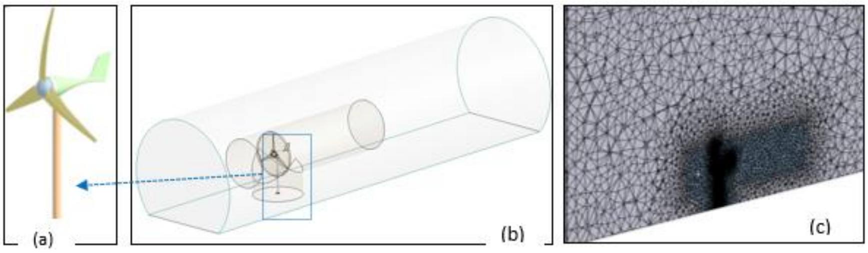

Figure 3. (a) Small wind turbine geometry, (b) the computational fluid domain and (c)cross-sectional mesh view.

The turbine rotor is composed of three slender blades attached to a hub, creating a rotor with a diameter D of approximately 1.2 meters as represented in **Error! Reference source not found.**(a) .The computational domain as shown in in **Error! Reference source not found.**(b) is designed to extend several diameters both upstream and downstream of the rotor to thoroughly capture the development of the wake. Specifically, the inlet is positioned about 3–4D upstream of the hub, the outlet is located around 10–15D downstream, and the lateral boundaries are set approximately 5–7D away from the rotor to reduce blockage effects. The domain's height also extends several diameters above and below the hub to accommodate vertical wake expansion. The rotor's geometry is meshed using a fine unstructured grid (tetrahedral/prism) around the blades and hub to accurately resolve the boundary layers. An O-type or C-type near-body mesh is typically employed around each blade to precisely capture the tip vortex and pressure gradients. In the far-field, the mesh is coarser but remains refined in the wake region. To ensure precise wall modeling, the mesh density is chosen so that y+ remains below 1 on the blade surfaces. This setup positions the first computational mesh cell within the viscous sublayer, facilitating accurate wall modeling, often referred to as "wall-resolved" simulation. This approach allows for the precise capture of complex near-wall phenomena such as flow separation, skin friction, and heat transfer without depending on empirical formulas, known as wall functions. Achieving a y+ of less than 1 requires a very fine and dense mesh near the blade surface, which, while more computationally demanding, is essential for high-accuracy aerodynamic simulations. In total, a mesh comprising roughly 1 million cells were employed as showed in **Error! Reference source not found.**(c), with increased refinement in areas close to the blades and the wake.

Boundary Conditions and Solver Setup

The CFD simulation utilizes a steady Reynolds-Averaged Navier–Stokes (RANS) solver (ANSYS Fluent) with pressure-based algorithms. The wind inlet is defined by a uniform velocity profile, such as 12 m/s for rated wind simulation and 50 m/s for extreme wind speed simulation, oriented perpendicular to the rotor plane. To replicate atmospheric conditions, a low upstream turbulence intensity, around 5–10%, may be applied. The outlet maintains a constant static pressure (atmospheric) with backflow turbulence intensity. Side and top boundaries are treated as slip walls, exhibiting zero normal gradient, to simulate an open field environment.

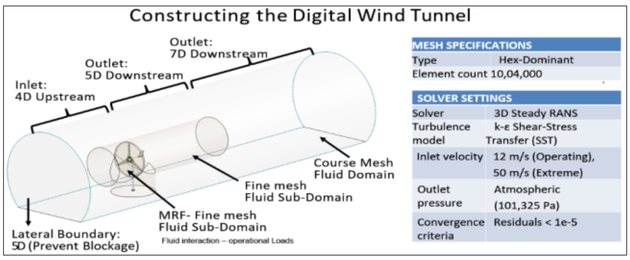

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Figure 4. Construction of digital wind tunnel for CFD simulation with solver settings.

The rotor is represented using a rotating reference frame or a sliding mesh to achieve the desired rotational speed that matches rated operating speed The hub and nacelle are modeled as solid no-slip regions. The equations are solved under steady-state conditions using an iterative solver (SIMPLE pressure–velocity coupling), with second-order discretization for both momentum and pressure. Convergence is tracked by residuals, typically less than 1e-5, and by observing integral quantities like torque or power. The total torque and thrust on the rotor are determined by integrating pressure and shear forces on the blade surfaces. These forces are then used as input loads for structural analysis. All CFD simulations are fully three-dimensional, although wake sli (b) from streamwise and cross-stream planes are extracted during post-processing to visualize velocity and pressure fields.

Turbulence Model Selection

Turbulence modeling is a crucial decision in the CFD analysis of wind turbines. Among the commonly used two-equation models are the standard k–ε and the k–ω shear-stress-transport (SST) formulations. In flows involving small rotors, the transition from laminar to turbulent boundary layers can occur on the blades, particularly at low tip-speed ratios. The transitional SST model (SST-γ formulation) has been identified as the most effective in capturing these effects on wind turbine blades [6][5]. In this research, we employ the k–ω SST model with suitable near-wall treatment, as it generally provides more accurate predictions of separation and stall on rotating blades. This choice aligns with recent studies: for instance, Younoussi and Ettaouil (2023) utilized the SST model in Fluent to analyze a three-bladed HAWT and found it to align well with anticipated performance trends [5]. Nonetheless, sensitivity tests with alternative models (e.g., realizable k–ε) were performed to ensure that wake predictions were not heavily influenced by the turbulence closure.

Therefore, the CFD model can be summarized as follows:

Solver & Turbulence Model: Steady-state RANS simulations utilizing the k–ω SST model were conducted to account for boundary-layer influences, pressure gradients, and flow separation.

Boundary Conditions

Inlet: A uniform velocity inlet was set at 12 m/s. , **Outlet:** A pressure outlet was established with static gauge pressure at atmospheric levels (101,325 Pa). Backflow pressure was defined as total pressure to ensure numerical stability. **Numerical Schemes:** Gradients were calculated using a least-squares cell-based approach; pressure was discretized with a second-order method; momentum was handled with second-order upwind to reduce numerical diffusion and maintain vorticity. **Convergence:** Pseudo–time stepping (global time step) was employed to achieve a steady-state solution.

RESULTS

Pressure Gradient and Vortex Structure

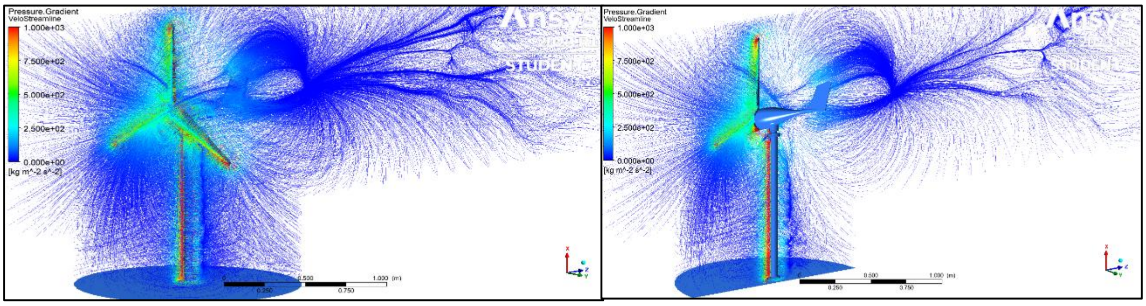

Figure 5. Pressure gradient built up and wake formation across near wind field under extreme wind speed.

0 (pressure-contours) depicts the static pressure distribution on the rotor and in the nearby wake. On the upstream side of each blade, a high-pressure area is observed, while a low-pressure suction zone is present on the downstream side. This pressure difference around the blade's cross-section creates the lift that generates rotor torque. These vortices spiral downstream from each blade tip and converge into a pair of concentrated vortex cores in the distant wake. Such tip vortices are a recognized characteristic of HAWT flows; they define the boundary of the low-momentum wake region[7]. The CFD streamlines clearly illustrate the development of these vortices, with their intensity determined by the blade loading. The wake shear layer, which is the region of high vorticity between the fast outer flow and the slower wake core, is also evident. This shear layer, dominated by the tip vortices, hinders the rapid mixing of high-momentum fluid into the wake[7], thus slowing down wake recovery.

Velocity Deficit and Recovery

Just after the rotor, the flow velocity in the wake is considerably lower compared to the freestream.

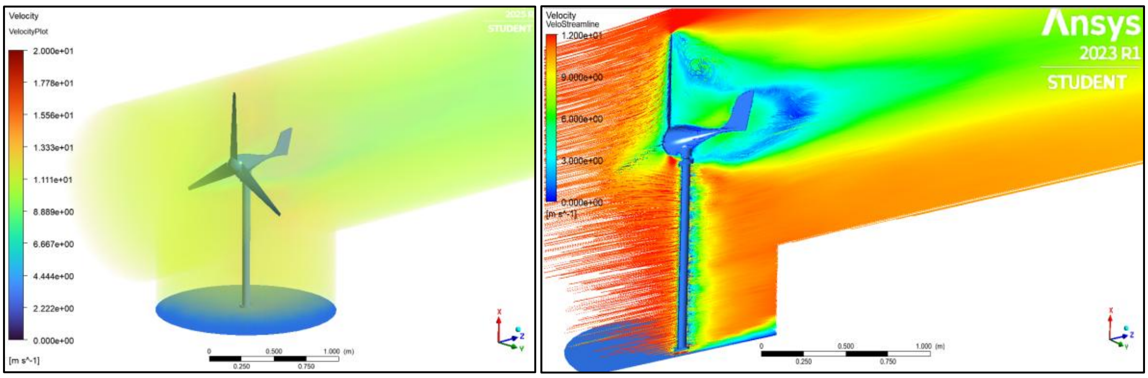

Figure 6. Velocity contours for full model and mid-plane section view in operating wind condition, scaled at 12 m/s

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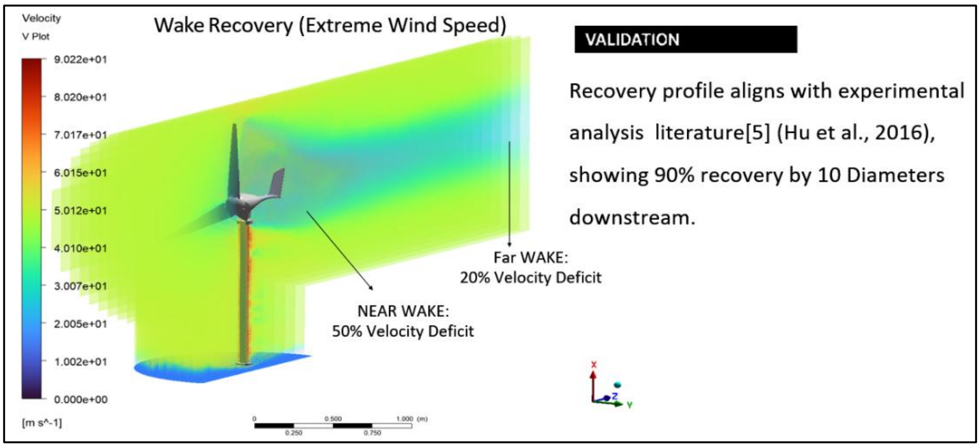

Figure 7. Velocity contours at mid-plane section view in extreme wind condition, contour scaled with max. 90 m/s.

0 and 0 shows CFD velocity contours, they illustrate a significant reduction of velocity on the turbine axis, with speeds frequently 30–50% less than the freestream at a distance of 1–3 rotor diameters downstream. This "velocity deficit" results from the energy extracted by the rotor. Further downstream, beyond approximately 5–10 diameters, turbulent mixing gradually introduces higher-momentum fluid into the wake, reducing the centerline deficit. Our simulations indicate that by 5–10D downstream, the deficit has partially recovered, aligning with wind tunnel and field measurements [8]. The deficit's spatial profile is uneven: it is most pronounced along the rotor axis and less so off-axis, reflecting the radial distribution of blade loading. Indeed, the peak deficit often occurs at the mid-span blade region where lift and induced downwash are greatest. This variation is consistent with experimental findings that show a higher deficit around the blade mid-span than inboard or outboard regions [9]. In this case, the deficit is about 40% at 2D downstream, decreasing to approximately 20% by 10D. As noted in wind energy literature, the slow wake recovery is influenced by the persistence of tip-vortex structures; only when these vortices break down (e.g., through the "leapfrogging" instability) does rapid mixing occur [7][10]. In our steady-RANS simulation, we do not explicitly resolve vortex breakdown, but the trend of gradual deficit decay aligns with the known physics.

Overall, the CFD results effectively capture the typical HAWT wake structure: a central low-velocity core surrounded by counter-rotating vortices, with a gradual return to ambient velocity [7].

Structural Analysis and Load Assessment

The integration of pressure and shear forces from the CFD model yields the distribution of forces on the blades and the loads on the hub. These forces are then applied to a finite-element model of the rotor assembly, which includes the blades, hub, and optionally the tower. The blade is modeled as either a composite shell or solid, depending on the desired level of detail. Under typical operational conditions, the blades undergo bending due to aerodynamic lift and twisting from torque.

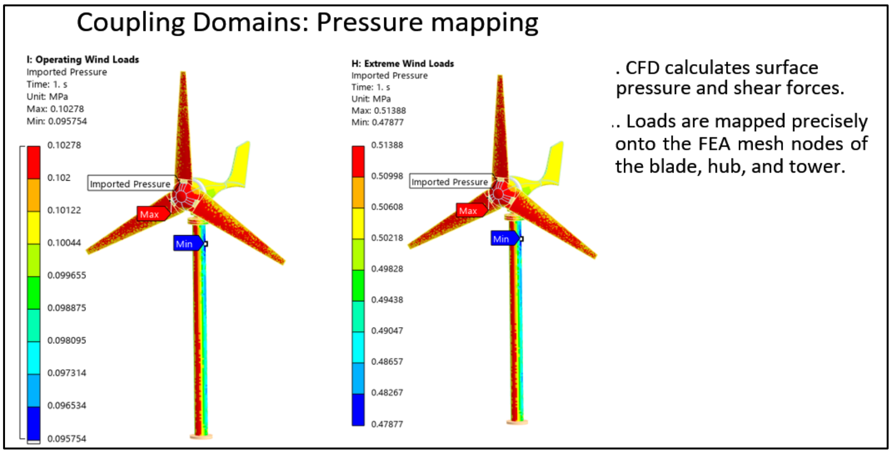

Figure 8. Pressure mapping on surface nodes of the structural components for operating and extreme loads,

0 shows the pressure mapping on nodes of the structural mesh of the wind turbine structure. This will map the aero-dynamic loads on the structure and further it can be utilized to check the strength of the structural components in respective wind load conditions. With these loads and fixed base at the turbine foundation, the system is solved in structural FEA solver and component results are extracted in respective load conditions.

Deformation and Stress

The FEA results show moderate elastic deformation. For instance, a 5 kW-class blade with a diameter of 3–4 meters deflect between 10 and 50 mm at the tip, with the exact deflection depending on the material's stiffness. This range aligns with published analyses: Deghoum et al. (2023) reported tip deflections of 18–46 mm for small HAWT blades made of carbon-fiber and glass-fiber composites[1]. In our study, blades made of carbon or fiberglass showed similar deflections in the tens of millimeters. Importantly, these structural displacements do not cause geometric stall or failure within the normal operating range, indicating adequate stiffness for low Reynolds-number conditions.

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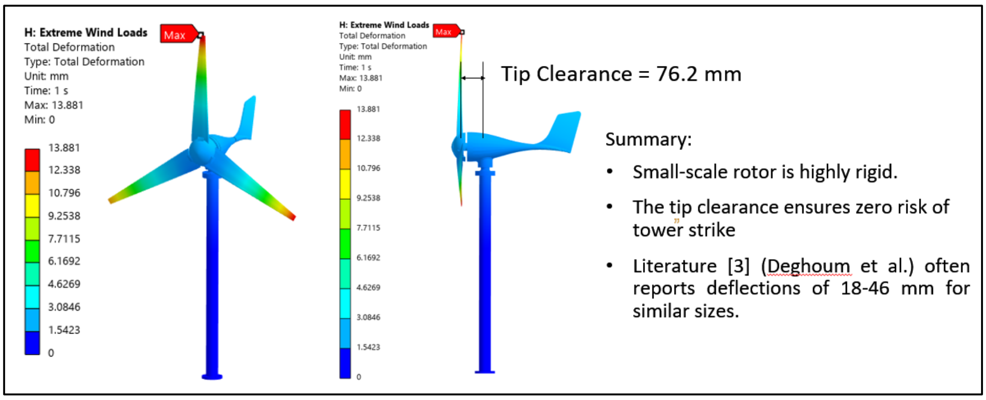
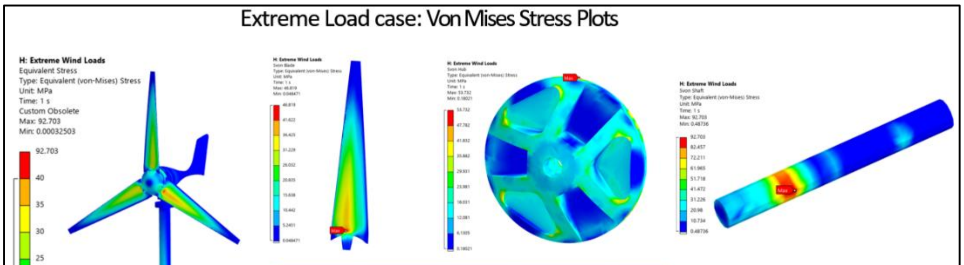


Figure 9. Deformation and tip clearance measurement in extreme load condition,

0 shows important criteria in wind turbine design subjected to the extreme wind condition, which are deflection of the blade tip and blade tip clearance. The maximum deflection at blade tip is 13.8mm which is aligned with the literature[3] which reports 18 mm deflection for similar size turbine. The lower deflections also suggest the wind turbine assembly is highly rigid due to its lower deflection under extreme wind loads. The blade clearance is 76 mm which is suffice to ensure zero risk of tower strike hence from deflection point of view this design validated for extreme wind conditions.

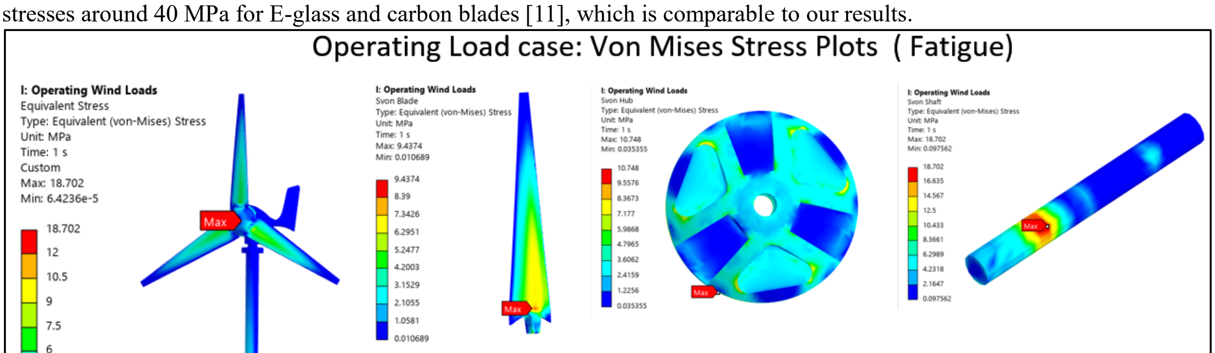
Design stresses in critical components



Component	Material	S von [Mpa]	Allowable Yield strength [Mpa]	SFu
Hub	Aluminum	55.7	90	1.62
Shaft	SS	92.7	205	2.21
Component	**Material**	**S1 [Mpa]**	**Allowable Yield strength [Mpa]**	**SFu**
Blade	Nylon 6-6	46.8	90	1.62

Figure 10. Design stresses in components subjected to the extreme load case and its safety factor,

The calculated von Mises stress distribution (0) highlights areas of peak design stresses on structural components. Consistent with other studies, the highest stress levels are found approximately at root of the blade, particularly on the outer fiber layers[2]. In our model, the maximum von Mises stresses were in the range of 46 Mpa to 92 MPa, depending on the material, which is well below the typical strength limit respective material. Minimum safety factor observed in blade which is 1.62 on blade. For example, Deghoum et al. found maximum stresses around 40 MPa for E-glass and carbon blades [11], which is comparable to our results.



Component	Material	S von [Mpa]	Allowable Fatigue strength [Mpa]	SFu
Hub	Aluminum	10.7	36	3.36
Shaft	SS	18.7	82	4.39
Component	**Material**	**S1 [Mpa]**	**Allowable Fatigue strength [Mpa]**	**SFu**
Blade	Nylon 6-6	9.43	28.8	3.05

Figure 11. Design stresses in components subjected to the operating load case (fatigue) and its safety factor,

The calculated von Mises stress distribution (0) highlights areas of peak design stresses on structural components. Consistent with other studies, the highest stress levels are found approximately at root of the blade, particularly on the outer fiber layers[2]. In our model, the maximum von Mises stresses were in the range of 9 Mpa to 18 MPa, depending on the material, which is well below the typical fatigue strength limit respective material. Minimum safety factor observed in blade which is 3.05 on blade.

DISCUSSION

Results were depicted through: Pressure gradient field combined with velocity streamlines: highlighting areas of high gradient, vortex formation, and wake expansion. Velocity magnitude slices throughout the domain: demonstrating momentum loss and wake recovery. Full-domain velocity slices: for inflow, wake development, and interaction with the ground.

Structural Analysis Mesh & Material: A detailed structural mesh encompassed the blades, hub, tower, and nacelle. Material properties, such as modulus and density, were assigned according to the turbine's construction materials, like aluminum, structural steel and composite (Nylon 6-6). Loads: Aerodynamic pressure distribution from CFD was applied to the structural model using a one-way coupling approach (i.e., pressures → FEA). Solver: Static structural analysis assessed deformation, von Mises stress.

Wake and Aerodynamic Flow

Pressure-Gradient & Streamline Visualization: The CFD analysis reveals significant pressure gradients near the leading edges and tips of the blades, where high lift is produced. These vortices remain intact for several rotor diameters before dissipating. A central wake region with low momentum flow emerges behind the rotor, interacting with the tower wake.

Velocity Deficit and Recovery: Velocity slices indicate a notable drop in velocity behind the rotor (wake deficit), especially near the hub and beneath the tower shadow. As the wake progresses downstream, the deficit gradually diminishes, and the core spreads laterally, suggesting momentum mixing and turbulent diffusion.

Structural Response

Total Deformation: The maximum deflection under extreme loads is approximately 13.8 mm, concentrated at the blade tips, while the tower remains mostly rigid. This suggests that the structure is adequately stiff for the operating conditions.

Von Mises Stress: The highest equivalent stress is around 46.8 MPa, located at the blade–hub junction, a typical high-load area. Considering blade composite materials, these stress levels are well within safety limits.

Comparison with Existing Studies

Several significant findings here are consistent with those documented in Scopus-indexed literature. Firstly, the prolonged presence of the wake several diameters downstream has been observed in wind farm studies [6]. Our CFD results indicate that the wake remains distinct beyond 5D, mirroring findings that upstream wake effects can reach approximately 10D [6]. The influence of tip vortices in delaying recovery is also well established, a phenomenon our steady RANS model qualitatively supports through the observed slow recovery trend.

Secondly, the stress distribution in the blades aligns with published analyses. The concentration of maximum stresses has been reported by other FEA studies of small blades [2]. The magnitude of stress (46.8 MPa) and tip deflection (13.8 mm) are similar to values found in the literature [1][11]. Deghoum et al. (2023) even compared different composite materials and found comparable levels of deflection and stress under rated loads [1][11]. Our findings reinforce the conclusion that typical composite materials (carbon/epoxy, glass/epoxy) offer sufficient strength margin for small rotors under normal operation.

Lastly, the overall integrated approach is in line with best practices in wind turbine analysis. Many recent studies (e.g., Zhang et al., 2024; Ismail et al., 2025) recommend using combined CFD and structural simulation to evaluate performance and design simultaneously [4] [5]. The novelty here lies in the detailed coupling of domain-wide flow results (pressure gradients and velocity profiles) with FEA loads. This approach provides a comprehensive view:

In urban or rooftop applications, the findings imply that turbine placement should consider the wake length to minimize turbulence impact on neighbors. Such considerations have been noted in distributed wind studies, which conclude that small HAWTs are most effective when properly sited and when their aerodynamic design is optimized for low-speed performance [4].

Applicability to Small-Scale Distributed Wind Systems

Small HAWTs are intended for distributed generation applications, such as on farms, within microgrids, and on buildings. Our findings highlight several practical considerations. Firstly, the basic three-blade rotors can achieve decent design safety at low wind speeds. This makes them appropriate for off-grid use or for supplementing local energy demands, although their energy production is modest compared to large-scale turbines. Secondly, the relatively low structural loads and deflections indicate that these turbines can be constructed from lightweight composites without incurring high costs. Since small rotors are subject to lower forces, the support structure can also be smaller, simplifying installation. Lastly, the wake analysis suggests that careful siting is crucial: placing a turbine too close behind another can result in reduced wind exposure.

In urban or village settings (as discussed by Ismail et al. (2025)), it is important to consider building-induced turbulence and wake overlap [4][5]. However, if properly arranged, clusters of small HAWTs could still make a significant contribution to local energy needs. Research has shown that while a single 300–500 W rooftop turbine offers modest savings, multiple units can substantially offset consumption [5]. In conclusion, the integrated CFD/FEA results presented here provide designers of distributed wind systems with confidence in the performance predictions and structural reliability of small HAWTs under realistic operating conditions.

CONCLUSION

An integrated analysis combining CFD and structural evaluation has been conducted on a small horizontal-axis wind turbine. The CFD findings shed light on the intricate wake flow, highlighting pressure gradients, and velocity deficits. The wake characteristics identified in this study is aligned with existing wind energy research [6][7]. Structural simulations, informed by CFD loads, indicate that the blades undergo moderate deformation and experience peak von Mises stresses on blade, yet these remain well within the material failure limits [1][2]. This suggests that standard composite materials are suitable for handling small rotor loads.

In summary, the findings validate that small HAWTs can be effectively modeled using current CFD/FEA tools. The insights into wake and stress behavior will aid in designing more efficient and reliable small turbines. Future research could expand these simulations to include unsteady flows, varying wind speeds, and innovative blade modifications (e.g., winglets or helical changes) proposed to influence vortex dynamics. The impact of turbulence and atmospheric conditions on wake recovery and structural fatigue also merits further exploration. Nonetheless, this study provides a solid foundation for small-scale turbine design and supports their viability as components of distributed renewable energy systems.This study involved a combined CFD–FEA investigation of a small-scale horizontal-axis wind turbine, offering valuable insights into both aerodynamic wake behavior and structural response under operational conditions. Velocity deficit plots indicated a pronounced near-wake core and gradual wake recovery, consistent with established research on miniature turbines. Structural analysis under the applied aerodynamic loads confirmed that maximum blade tip deflection remains under 13.8 mm, while peak von Mises stress (≈ 46.8 MPa) was found at the hub–blade junction, well within safe limits for typical structural materials.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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