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Evaluating Mechanical Strength in Vertical-Axis Tidal Turbines: A Comparative Study of Internal Blade Structure and Material Selection through CFD Simulation

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Abstract. Due to the density of water, tidal turbine blades are subject to significantly greater stresses than wind turbine blades. Multiple blade failures occurred during prototype testing as a result of loading conditions and protracted exposure to seawater, which created a severe work environment. The structural integrity of tidal turbine blades is essential for long-term reliability and performance. Numerous investigations into structural performance have been conducted. However, previous research has centred on horizontal-axis tidal turbines, while research on small-scale vertical-axis tidal turbines is limited. This paper aims to compare the Vertical-Axis Tidal Turbine (VATT) structural performance of hollow and solid blade structures in an identical NACA profile using three distinct materials. Finite element analysis (FEA) is employed to construct a model and simulate the mechanical characteristics of VATT blades. The use of static analysis simulation is employed in order to evaluate many parameters, including stress distribution and deflection. Parametric studies are conducted to explore the impact of internal blade structure and materials on mechanical strength. The use of computational fluid dynamics (CFD) simulations is employed for the purpose of analyzing the interaction between blades of vertical axis tidal turbines (VATT) and tidal currents, thereby enabling the assessment of structural loading. According to the simulation results, the hollow profile is subject to significant deflections and stresses. Other data indicates that the utilization of stiffeners in porous structures improves material efficiency and results in lighter blades, although further analysis is needed to investigate fatigue life prediction in optimizing structural design.

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1 Introduction

Tidal energy, as a form of marine renewable energy, possesses significant potential owing to its high level of reliability, superior energy density, assuredness, and durability. The harnessing of tidal energy, which involves converting the predictable vertical movements of water and subsequent tidal currents into kinetic energy, has the potential to be utilized as a renewable power source (1). However, due to the high density of water, the stresses on the tidal turbine blades are significantly greater than those experienced by wind turbine blades, and the combination of high currents and wave loading results in a large number of cycles (around 108 in 20 years). Several blade failures have occurred during prototype testing as a result of these loading conditions and permanent immersion in seawater, which create an exceptionally severe environment (2). In line with this statement, a review paper (3) analyses a total of 58 instances of tidal stream electricity deployments spanning the time period from 2003 to August 2020. The findings indicate that the primary cause of failure was blade failure, with generator and monitoring failures being the subsequent most common causes. The primary cause of blade failures was attributed to inaccuracies in load estimation during the design phase. Hence, it is crucial to conduct an in-depth analysis of the shortcomings of blade construction.

This paper centers its attention on the examination of small-scale vertical-axis tidal turbines intended for deployment in regions characterized by low-to-moderate flow velocities. VATTs deliver better power densities than Horizontal Axis Tidal turbine (HATTs) in areas with low-to-moderate speeds (4). Furthermore, in a remote area there will be limited regional infrastructure for turbine assembly, and limited supporting equipment facilities (cranes, barges, etc.) (5).

Several studies have been conducted on the analysis of structural performance. However, the focus of existing studies has primarily been on horizontal axis tidal turbines. For instance, one study examined the structural performance of a composite turbine with a NACA 4415 airfoil (6) and the results indicate that the blade root region is subjected to elevated stress levels, which may result in failure modes such as resin cracking, interfacial debonding between fibers and matrix, delamination, and fibre breakage. In order to maintain an equivalent safety factor, it is predicted that glass fibre-reinforced composite blades will require laminates that are approximately three times thicker than those of carbon-fibre reinforced composite blades. The same NACA 4415 aerofoil for two commercial scale glass fibre reinforced composite (GFRP) blades (1.50 MW and 0.35 MW) has been analyzed to predict its fatigue life (7). Another study investigated the impact of water depth and turbine rotational speed on the structural performance of horizontal stainless steel turbine blades (8). The effect of velocity profile on the load variation and fatigue life of large-scale steel horizontal tidal turbines are analyzed by (9), and influence of different tip speed ratio of Stainless steel HATT to the performance curve, pressure distribution on the blade, and velocity streamline was done by (10).

A study on vertical-axis tidal turbines blade (11) investigates the relationship between the profile of the blade and the mechanical force generated, particularly. The variable under consideration is the profile type of the blade, which is determined by comparing symmetrical and asymmetrical NACA straight blade types under the same climatic conditions. It has been observed that the profile of the blade has an effect on the structure's tension levels. This effect is more pronounced in asymmetrical blade profiles, which generate a larger lift force than their symmetrical counterparts. Another A recent study conducted by (12) investigated the structural behavior of the turbine under varying free-stream velocity values and turbine rotational rates. One of the findings of this research indicate that the strut, blade-strut junction, and strut-shaft joint are crucial components of the turbine that necessitate meticulous design considerations. Additionally, the study proposes that maintaining a hollow structure for the turbine blade might effectively decrease the weight of the turbine. It is worth noting that it is advisable to utilize steel or a material possessing exceptional rigidity and strength for the construction of the inertia, turbine struts, and shaft. Therefore, this paper aims to conduct a comparative analysis of the structural performance of hollow and solid blade structures in a identical NACA profile using three distinct materials. The acquired data will be evaluated with consideration to stress, deflection, weight, and corrosion. The selection of the proposed profile and material will be determined by combining the weighted results with the simulation results.

2 Method

The ultimate objective of this study is to explore the structural response of various blade materials and internal structures for the NACA0021 profile. The selection of this particular NACA airfoil was based on a prior analysis (11) that involved a comparison of NACA 0015, NACA 4415, ILH 166, and NACA 0021 airfoils. The findings indicated that the NACA 0021 airfoil possessed the maximum moment of inertia. This observation suggests that the airfoil has enhanced resistance to bending, resulting in reduced levels of bending stress and deflection.

The acquired data will be evaluated in Table 1 with consideration to stress, deflection, weight, and corrosion. The selection of the proposed profile and material will be determined by combining the weighted results with the simulation results.The following table presents the evaluation of stress, deflection, weight, and corrosion factors in the selection process of materials for the production of Darrieus marine current turbine blades.

Table 1. Weighting in blade design

Parameter	**Score**
Stress	Higha
Deflection	Lowb
Weight	Low
Corrosion	High

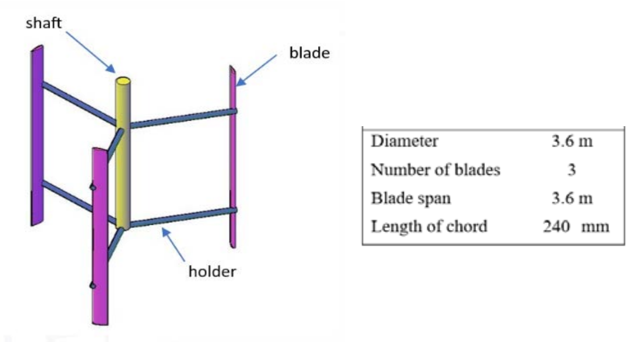
The stress parameter is assigned a high value due to the necessity for the blades to endure the mechanical loads imposed by the ocean currents. The deflection parameter is assigned a modest value due to the undesirability of excessive blade bending in response to these forces. The weight attribute is assigned a lower score due to the higher efficiency of lighter blades in harnessing energy from ocean currents. The corrosion parameter is assigned a high rating due to the anticipated exposure of the blades to seawater, which has the potential to induce corrosion.

In order to accomplish this goal, a Fluid-structure interaction (FSI) analysis was performed to make a prediction about the pressure distribution on the blade. Following that, the hydrodynamic load that was determined from the CFD analysis was transferred to the FEA model in order to investigate the structural response of the blade

2.1 Geometric Model, Blade structure and Material Selection

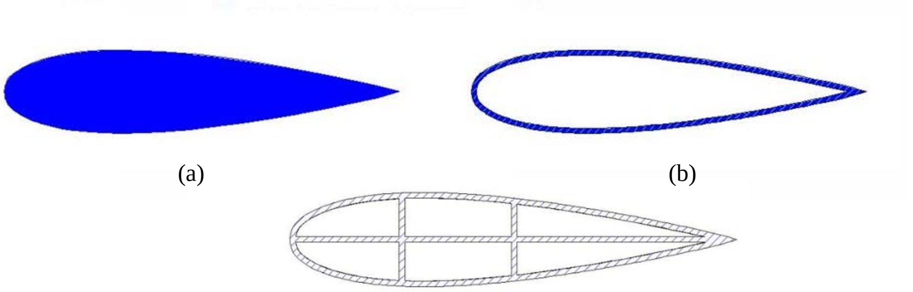
According to the findings of the research conducted by (13), a three-blade darrieus rotor typically offers a higher maximum coefficient of power when compared to a four-blade rotor. This led to the decision to use a darrieus turbine with three rotor blades. The geometric model and the dimension of the vertical axis tidal turbine being examined can be seen in Figure 1.

The type of blade that is being researched in this article is a symmetric type called NACA0021. It is made of three distinct materials, and it has two different blade structure types: solid and hollow. Figure 2 depicts the hydrofoil blade's cross-section for both the solid and hollow blade structures of the hydrofoil.



Diameter	3.6 m
Number of blades	3
Blade span	3.6 m
Length of chord	240 mm

Figure 1. Vertical Axis Tidal Turbine Geometric Model and dimension


(a) (b)

(c)

Figure 2. Hydrofoil blade NACA0021 sectional image for (a) solid, (b) hollow and (c) hollow with stiffener structure; hollow and stiffener blade thickness is 3 mm.

Different material for a Tidal Turbine has been chosen with several considerations. A study to evaluate the environmental impact of a range of materials for tidal stream turbine blades was done by (14) covering glass fiber composite turbine blades, steel blades, Carbon fibre composite blades and suggested that bio-based fibers and recyclable resin as a way to reduce the environmental impact of tidal turbine blade manufacturing. This investigation, on the other hand, will concentrate primarily on three materials that are typically utilized: stainless steel, aluminum, and carbon fiber composite.

2.2 Boundary Condition and Simulation Model

The Darrieus turbine employs blades featuring aerofoil portions to generate aerodynamic lift. The turbines possess the ability to transform the lift produced by their blades into a favorable torque when they rotate at a speed that is adequately high in relation to the fluid flow in their vicinity. When the rotor undergoes rotation, it experiences a dynamic change in the relative flow, which is the combined vector of the local stream flow and the velocity of the blade. A free stream flow induces an angle of attack denoted as θ. The relative flow's angle of attack and velocity magnitude are influenced by the foil's orbital position, commonly known as the azimuthal angle (α). The hydrodynamic forces encountered by a rotating blade exhibit fluctuations in response to changes in its local angle of attack, as depicted in Figure 3.

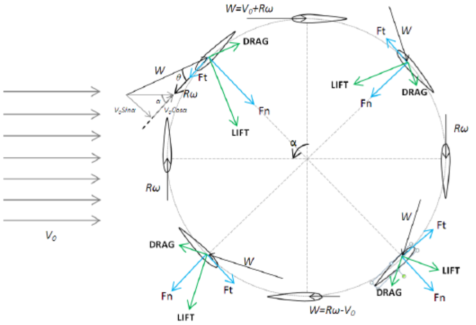


Figure 3.The hydrodynamic forces acting on the blade at various azimuth positions (15)

Figure 4 provides an overview of the computational domain as well as the selected boundary conditions that were used in the simulations of computational fluid dynamics. The computational domain is split into two distinct zones: the outer zone, which is a region that is always in the same position, and the inner zone, which is a region that is always in motion. The diameter of the turbine, denoted by the letter D, is the subject of the measurements displayed in Figure 4.

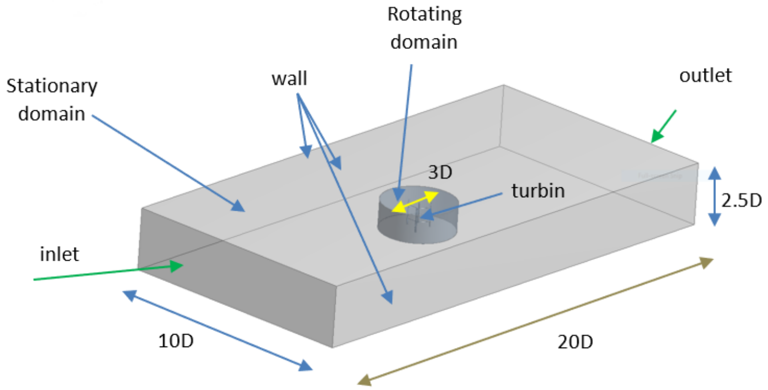


Figure 4. Nomenclature pertaining to the boundaries of the simulation domain.

RANS techniques are the turbulence models commonly employed for conducting computational fluid dynamics (CFD) study on vertical-axis hydrokinetic turbines. The development of the SST model was motivated by the need for models capable of accurately simulating aeronautical flows characterized by pronounced unfavorable pressure gradients and boundary layer separation. In order to achieve this objective, the Shear Stress Transport (SST) model integrates the k - ω model in regions next to solid walls (16).

In the simulation, the speed of the ocean water was adjusted to be five meters per second. Figure 5 illustrates the orientation of the blade in relation to the azimuth axis of the vertical turbine. The blade is portrayed as being positioned in a manner that is contrary to the direction of the flow of the sea current.

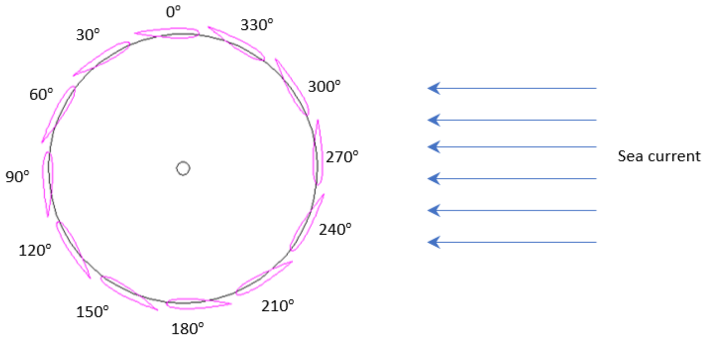


Figure 5. Orientation of the blades with relation to the sea current

3 Result and Discussion

In order to ascertain the pressure exerted on the blade, it is essential to possess knowledge of the velocity profile that transpires at all points along the blade. Figure 6 illustrates the velocity profile as it traverses the blade at that specific moment in time. The experiment involved conducting a simulation at four discrete locations, each of which was rotated by an angle of 30 degrees. In each of these distinct positions, the blade will experience a certain set of loads.

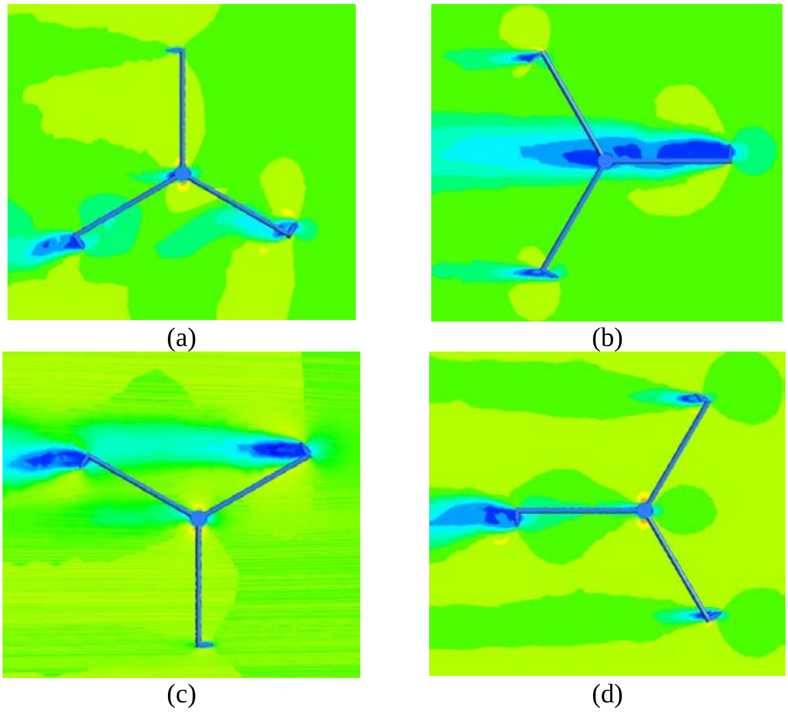


Figure 6. Profile of the velocity passing through the blade

Figures 7 and 8 depict the stress and deflection patterns observed in the blades at 30-degree intervals. Blades with a hollow shape exhibit the highest levels of stress in comparison to other blade types, particularly when positioned at 0 degrees. However, it is observed that the composite material with a stiffener exhibits a higher value at specific positions, with the stainless steel material with a stiffener ranking first at the 300-degree position. Upon analyzing the above-mentioned data, it becomes evident that hollow blades experiencing excessive stress are more prone to damage.

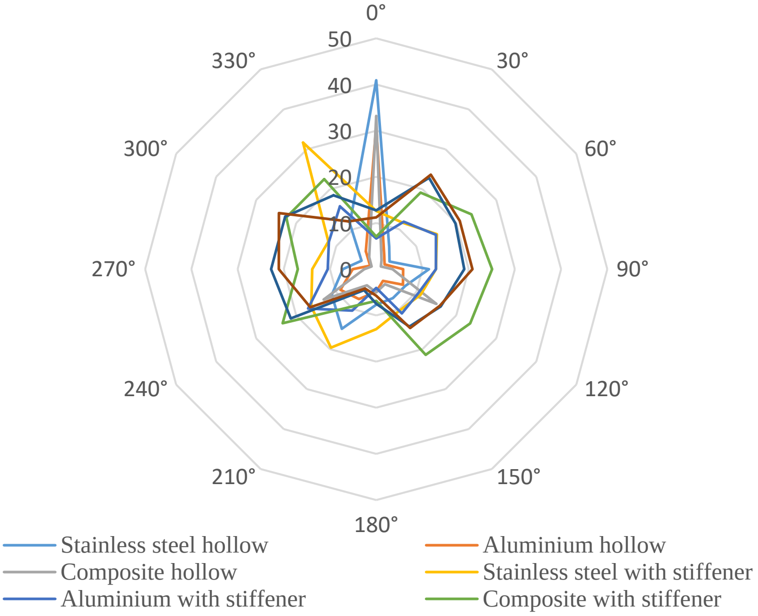


Figure 7. Bending Stress of the blade in MPa based on its position at azimuth points for three different materials.

In the context of the hollow-shaped blade, it is seen that significant deflection is present at the angular points of 90, 210, and 330 degrees. However, when examined holistically, it can be shown that carbon fiber composites reinforced with stiffeners have comparatively significant deflections. Solid blades typically exhibit a notable degree of strength, while materials such as stainless steel and aluminum possess the ability to offer effective protection against corrosion. Nevertheless, it is worth noting that solid blades may possess a greater weight compared to their hollow counterparts, perhaps leading to implications for the overall performance of the turbine. The implementation of hollow blades has the potential to decrease the overall weight of turbines, hence enhancing their efficiency. The incorporation of stiffeners into hollow blades has the potential to enhance both the strength and structural stability of the blade. The utilization of these blades may result in reduced deflection rates and stresses, which can be attributed to the enhanced structural integrity of the stiffener in comparison to conventional hollow blades. Table 2 provides a concise overview of the mean value of the simulation outcomes. The observation of elevated deflection values in composites using stiffeners necessitates careful consideration.

Table 2. Summary of deflection and stress of blade profile and material.

Blade profile	Material	Deflection, mm	Stress, MPa
solid	Stainless Steel	2.79	16.91
	Aluminium	3.77	15.96
stiffened	Stainless Steel	2.69	14.99
	Aluminium	3.26	11.45
	Composite	8.22	18.44

Hollow	Stainless Steel	3.69	10.99
	Aluminium	4.25	7.02
	Composite	5.24	7.33

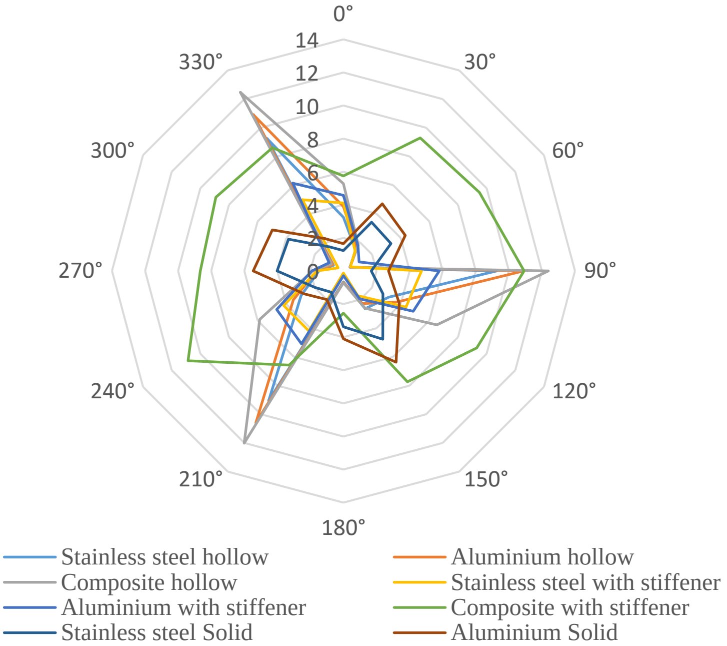


Figure 8. Deflection of the blade in mm based on its position at azimuth points for three different materials.

Table 3 is the scoring for the parameters of stress, deflection, weight, and corrosion resistance when specifying materials for manufacturing Darrieus-type marine current turbine blades. The higher the score, the better the material performs in that parameter.

Table 3. Scoring of parameters on blade performance

Material	**Stress (scale 1-10)**	**Deflection (scale 1-10)**	**Weight (scale 1-10)**	**Corrosion resistance (scale 1-10)**
Stainless Steel Solid	5	7	3	7
Aluminium Solid	6	7	4	6
Stainless Steel Hollow	4	6	3	7
Aluminium Hollow	4	6	4	6
Carbon Fiber Hollow	4	5	9	5
Stainless Steel Hollow with Stiffeners	5	8	3	7
Aluminium Hollow with Stiffeners	7	7	5	6
Carbon Fiber Hollow with Stiffeners	6	5	8	5

The aluminum material with stiffener yields the highest result when the weighting factor is multiplied by the score in Table 3, with the composite material with stiffener coming in second place. The material's excellent qualities, namely its great corrosion resistance and light weight, render it more advantageous compared to carbon fiber. It is widely acknowledged that carbon fiber is prone to infiltration by seawater (17,18), thus necessitating the implementation of a coating technique.

4 CONCLUSION

The present study employed computational fluid dynamics techniques and mechanical procedures to examine the interaction between ocean currents and vertical-axis tidal turbine systems. The primary objective was to evaluate the structural effects resulting from the utilization of various blade profiles and materials. The findings from the simulation indicate that the hollow blade exhibited the greatest magnitude of stress and deflection, with the solid blade ranking second in terms of these measures. Subsequent investigations have revealed that the implementation of a hollow construction accompanied by stiffeners has the potential to enhance material efficiency while enabling the manufacturing of blades with reduced weight. Further investigation is necessary to validate these findings. This research's findings can also serve as a basis for assessing fatigue life predictions while focusing on structural design optimization.

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