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Recent Advancements in Ocean Current Turbine Blade Design: A Review of Geometrical Shape, Performance and Potential Development using CAE

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Abstract

The global energy demand is experiencing a significant surge, reaching 442 exajoules in 2023. The urgency to develop renewable energy sources intensifies as global energy needs continue to escalate, coupled with the detrimental impact of fossil fuel consumption on climate change. Ocean current energy has emerged as a promising renewable energy source due to its predictability and minimal environmental impact. However, the efficiency and reliability of Ocean Current Turbines (OCTs) depend highly on their blades' design and performance. This review provides a comprehensive overview of recent advancements in ocean current and tidal current turbine blade design and the challenges and issues associated with their operation and maintenance. The paper discusses various design aspects, including blade geometry, material selection, hydrodynamic performance optimization, and bio-inspired designs. Additionally, it highlights the common failures and degradation mechanisms of turbine blades, such as fatigue, erosion, and cavitation. Furthermore, the review explores the challenges faced in developing and deploying OCTs, such as improved blade durability, cost-effectiveness, and environmental compatibility.

1 Introduction

Global climate change and rising energy demands drive the search for sustainable and environmentally friendly renewable energy sources. According to a 2023 report by the International Energy Agency (IEA), Total Final Consumption (TFC) of energy reached 442 exajoules and is projected to continue increasing by 1.1% annually until 2030, followed by a slower growth rate until 2050 [1]. Notably, fossil fuels still need to meet over 80% of global energy needs. Using fossil fuels produces high CO_2 emissions, contributing significantly to climate change. Recent decades have marked the hottest period, with the average global temperature rising by approximately 1.17 °C compared to the pre-industrial era. In response to this evidence, various international conventions and agreements have been established to address climate change. The Kyoto Protocol and the Paris Agreement on climate change are significant agreements to reduce greenhouse gas emissions.

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The Paris Agreement, signed in 2015, sets a target to limit the global temperature rise to below 1.5 °C. Furthermore, many countries have committed to achieving net-zero emissions by 2050, meaning removals or reductions will balance their greenhouse gas emissions. Renewable energy holds immense potential for reducing carbon emissions, but high initial costs and inadequate infrastructure still hinder its implementation [2-5]. Based on studies of various options, ocean energy has attracted attention as a promising energy source [6-8]. Using ocean current energy not only promises a sustainable energy source but also contributes to efforts to reduce dependence on fossil fuels. One of the critical technologies in utilizing ocean current energy is the Ocean Current Turbine (OCT), which captures kinetic energy from ocean currents. An ocean current turbine is a device that resembles a windmill but operates underwater. This turbine consists of a rotor with blades that rotate to produce torque on the shaft, which is then converted into electrical energy through a generator. The technology offers several advantages over other renewable energy sources. Ocean currents are more consistent and predictable than wind and solar, enabling more sustainable and reliable operations [9-11].

The energy potential of ocean currents is enormous (see Figure 1). However, harnessing this potential requires the development of efficient and economical harvesting technology [12]. The design of ocean current turbine blades plays an essential role in determining the overall efficiency and performance of the turbine system. A well-designed blade can improve energy capture and optimize the conversion of kinetic energy into mechanical energy. However, ocean current turbine blade designs face several complex technical challenges. Variable ocean currents, harsh operating conditions, and the need to minimize environmental impact were some of the factors that needed to be considered in the design process [13-16].

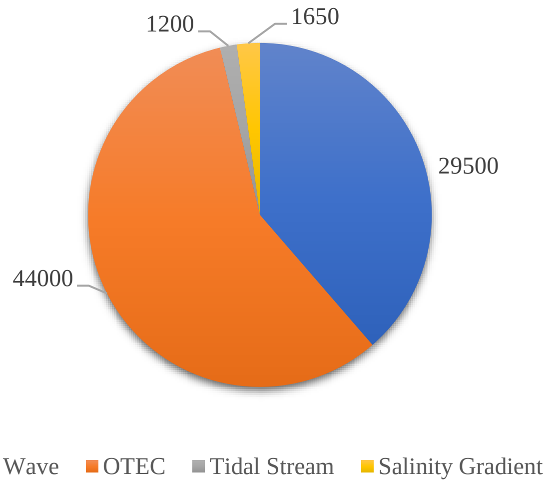


Figure 1. Ocean energy potential (TWh/Year) [17]

In recent years, significant advances have been made in the design of ocean current turbine blades. Material innovations, computational modeling techniques, and experimental test methods have enabled researchers and engineers to develop more efficient and durable turbine blades. However, despite progress, many challenges still exist to ensure this technology can be widely and economically implemented [14]. This article reviews the recent advances and challenges in designing current turbine blades for the ocean. The discussion will include material innovation, design techniques, and evaluation of the performance and sustainability of turbine blades.

In contrast to previous studies, this review endeavors to elaborate on critical challenges that are often only superficially mentioned in prior works. Furthermore, this paper highlights the need to enhance blade durability, cost-effectiveness, and environmental compatibility, offering a more integrated approach to addressing these issues. Suggested future research directions encompass adaptive control technologies and real-time monitoring systems, which should be discussed more in the existing literature. This comprehensive review synthesizes existing knowledge and identifies and addresses gaps in the current research landscape.

2 Ocean Energy

Ocean energy is energy derived from the movement and properties of seawater, such as waves, ocean currents, tides, thermals, and salinity gradients (see Figure 2). This energy can be processed into sustainable and environmentally friendly electrical power, with great potential to help overcome the global energy crisis.

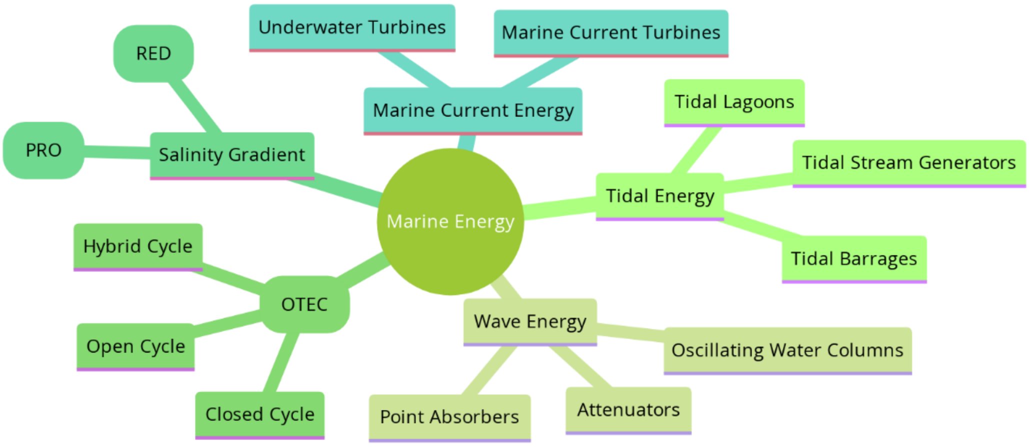


Figure 2. Various types of ocean energy

Several countries have demonstrated significant progress in developing technologies to harness ocean energy. The United Kingdom has successfully developed and operated the MeyGen project, one of the world's most significant tidal stream power projects. This project can generate enough electricity to meet the energy needs of thousands of households. The turbine blade design used in this project has significantly evolved from fixed blades to adjustable-pitch blades, enhancing energy capture efficiency and reducing mechanical stress on the turbines [13,18,19]. Meanwhile, South Korea has also made strides with the Sihwa Lake Tidal Power Station, which generates 254 MW of electricity, making it the largest tidal power station in the world [9,13]. France is another crucial player in this sector. The Paimpol-Bréhat pilot project uses wave energy with up to 2 MW capacity. The turbine blade design in this project has transitioned from conventional materials to more durable and lightweight composite materials, increasing efficiency and turbine lifespan. This project is part of the country's efforts to boost the contribution of renewable energy to the overall national energy mix. It aims to generate electricity and collect valuable data that will help further optimize the technology. Ocean energy technology development is projected to grow, with a global capacity target of 350 GW by 2050. This growth is driven by the need for clean, local, and predictable energy sources expected to support the decarbonization of global energy systems fully [13,20].

2.1 Wave energy

Wave energy is a form of renewable energy produced from the movement of ocean waves. Ocean waves are formed by wind blowing on the sea's surface, transferring energy to the water and creating moving waves. This energy can be harnessed to generate electricity, offering a sustainable and environmentally friendly energy source. Wave power density is the most commonly accepted measure of natural wave energy resources. The linear length of the wave crest, the wave height, and the wave period were calculated. The wave power density is defined as in Equation 1.

$$Wave\ power\ density\ (in\ \frac{kW}{m}) = \frac{P}{L} = kH_S^2T_z \tag{1}$$

The power of the wave of the linear crest length L is P, the significant wave height is H_s in meters, the mean zero-crossing wave period is T_z in seconds, and the constant k is about 0.4-0.6, which depends on the relative amounts of energy in short-period wind-driven waves and long-period swells in a given sea state. Ocean waves contain two forms of energy: kinetic energy, which comes from the movement of water, and potential energy, which is generated by the height of the wave. Wave energy harvesting technology is designed to capture these two types of energy and convert them into electrical energy. Several commonly used device designs include point absorbers, oscillating water columns, attenuators, and overtopping devices [21,22].

2.2 Ocean current

Ocean current energy or ocean current energy is a form of renewable energy that utilizes kinetic energy from ocean currents to generate electricity. Ocean currents are generated by a combination of factors, such as water movement due to Earth's rotation, tides, and interactions with the geological structure of the seafloor. This technology offers a sustainable and environmentally friendly energy source with great potential to meet global energy needs [23]. The energy of ocean currents is obtained by utilizing the constant movement of water below the sea's surface. These currents contain kinetic energy that can be captured and converted into electrical energy using ocean current turbines. The working principle is similar to that of a wind turbine, but it uses the movement of water as an energy source.

2.3 Tidal current

Tidal currents are horizontal movements of water caused by the rise and fall of tides. These currents are most substantial in coastal areas, estuaries, and channels where water movement is concentrated. The MeyGen project in Pentland Firth, Scotland, is one of the most significant tidal energy projects. MeyGen successfully installed several turbines with a production capacity of up to 28 MW, proving that tidal energy is feasible for large-scale production [13,18]. The kinetic energy of these currents can be captured and converted into electricity using underwater turbines. However, the harvesting technology requires support structures like tidal lagoons and barrages. The momentum theory can be used to calculate the amount of power a turbine can extract from an unbounded fluid flow (see Equation 2).

$$P = \frac{1}{2}\rho A C_p u_\infty^3 \tag{2}$$

Where P is the power generated (W); ρ is the seawater density (kg/m^3); A is the swept area of the turbine (m^2); C_p is the power coefficient of the turbine (dimensionless); and u_∞^3 is the free stream velocity (m/s).

2.4 Salinity gradient energy

The salinity energy gradient is based on the principle of osmosis, in which water with a lower salt concentration (freshwater) moves through a semipermeable membrane towards the water with a higher salt concentration (seawater) to balance the concentration. This process creates osmotic pressure that can be converted into mechanical energy and electricity. The two main methods of harnessing this energy are Reverse Electrodialysis (RED) and Pressure Retarded Osmosis (PRO). The development and installation of salinity gradient energy systems require significant investments, especially in membrane technology and infrastructure, so they are still not economical to implement [17].

2.5 Ocean thermal energy conversion

Ocean Thermal Energy Conversion (OTEC) is a technology that utilizes the temperature difference between warm sea surface water and cold deep ocean water to generate electricity. The potential for this energy is enormous, especially in the tropics, where the temperature difference between surface and ocean depths is significant. OTEC works on the principle of thermodynamic cycles, where temperature differences are used to drive turbines and generate electricity (see Figure 3). The technology offers sustainable and environmentally friendly renewable energy solutions but faces various technical and economic challenges [24-26].

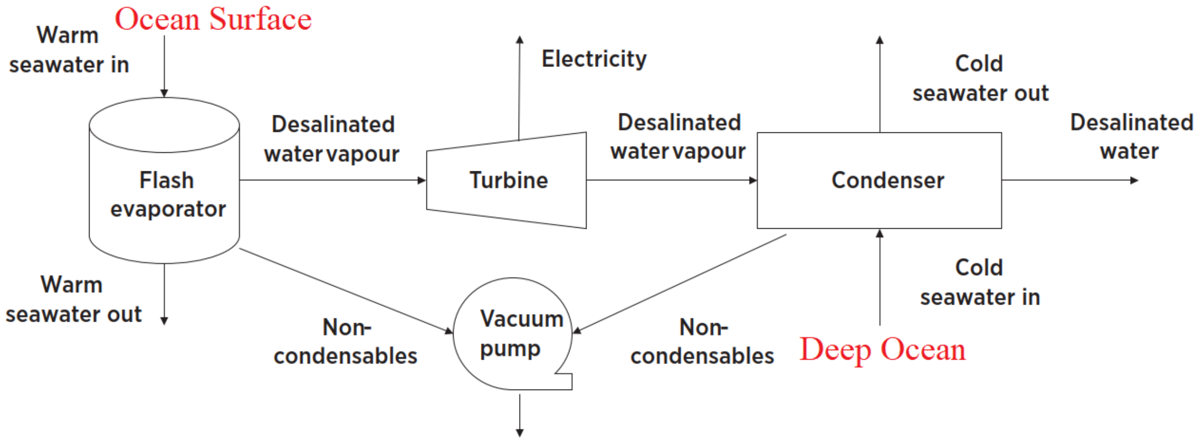


Figure 3. Open – Cycle OTEC system [24]

3 Turbine Blade Designs for Ocean Current

By harnessing ocean current’s steady and constant power, ocean current turbines function similarly to wind turbines but are placed below the water's surface. One of the main components of an ocean current turbine is the blade, which plays an essential role in converting kinetic energy from ocean currents into mechanical energy. This section will discuss the design of ocean current turbine blades in depth by focusing on three main aspects: blade geometry or shape, material selection, and hydrodynamic response. In addition, differences in axis orientation and turbine shape must be understood as one of the considerations in the study. In-depth knowledge of these aspects is essential for designing efficient, durable, and reliable OCT blades.

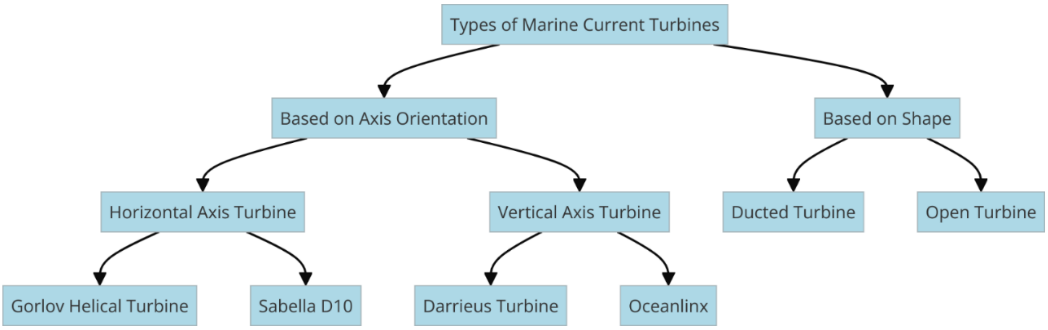


Figure 4. Various types of ocean current turbines

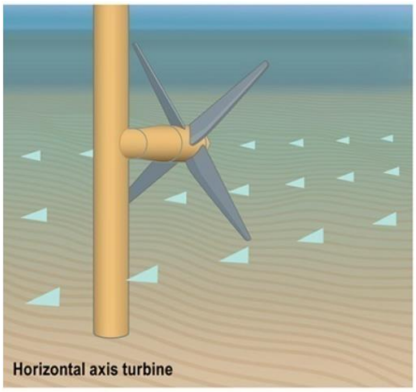


Figure 5. Ocean current turbine's axis orientation [27]

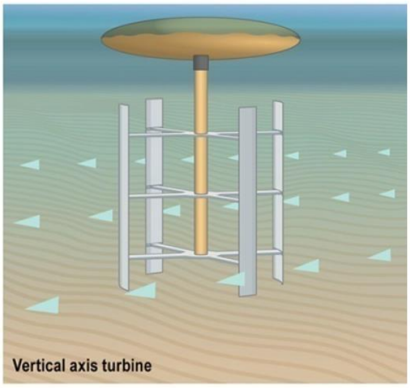


Figure 5. *Cont*.

Figure 4 shows a diagram of the classification of types of ocean current turbines based on two main criteria: axis orientation and shape. Based on axis orientation, ocean current turbines are divided into Horizontal axis turbines and vertical axis turbines (Figure 5). An example of a horizontal axis turbine is Voith Hydro, shown in Figure 6 (a), while an example of a vertical axis turbine is East Coast Oil and Gas (EC-OG), as depicted in Figure 6 (b). Based on their shape, ocean current turbines are classified into two types: Tunnel Turbines and Open Turbines. These diagrams help understand the variety of turbines used to harness energy from ocean currents, showing the different designs and technologies used in each category.


a b

Figure 6. Turbine: (a) Voith hydro, and (b) EC – OG subsea power hub [9]

3.1 Blade geometry

The geometry of OCT blades is fundamental to determining their aerodynamic performance. Factors such as blade profile, tilt angle, and blade length must be optimized to maximize power generated from ocean currents. Geometric design considerations must also consider environmental factors, such as current velocity and turbulence.

3.1.1 Shape and profile optimization

Optimization of the Shape and profile of ocean current turbine blades has been a primary focus in improving turbine efficiency and performance. Optimal hydrofoil design is essential to minimize drag, increase lift, and avoid destructive cavitation phenomenon. Hydrofoil profiles often used in ocean current turbine design (refer to Figure 7) include the National Advisory Committee for Aeronautics (NACA) series, which has been shown to provide good aerodynamic performance. Several recent studies have focused on developing new hydrofoils and profile modifications to perform better in variable ocean current conditions.

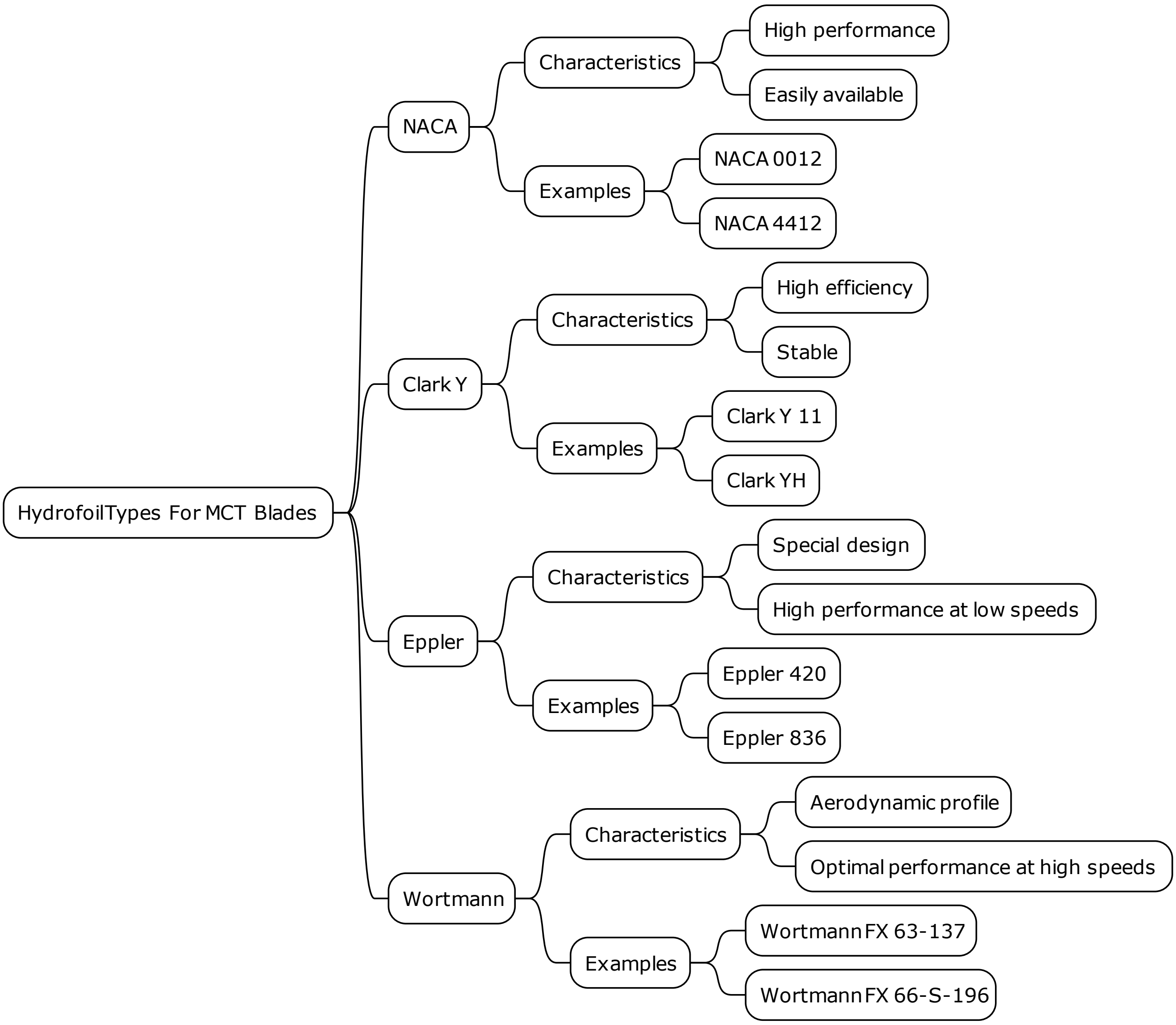


Figure 7. Various types of hydrofoils for OCTs

For example, the study by Chu et al. [28] developed a biomimicry turbine design based on Dryobalanops Aromatica seeds, showing improved hydrodynamic performance and torque compared to conventional turbines. In addition, using genetic algorithm-based optimization techniques and swarm particle optimization has resulted in hydrofoil designs capable of reducing cavitation phenomena and increasing lift-to-drag ratios [29]. The CFD software, such as OpenFOAM for hydrodynamic simulation, has enabled a more efficient and accurate assessment of hydrofoil profile performance. Several studies have shown that simulations using OpenFOAM can provide results close to experimental results, with advantages in terms of time and cost [30].

3.1.2 Tip and root designs

The tip and root blade design also play an essential role in the overall performance of the turbine. Well-designed blade tips can reduce losses and improve aerodynamic efficiency. Innovative blade tip designs, such as wing-shaped tip blades, have been shown to improve performance by lowering blade tip vortices [31]. For the root part of the blade, special attention is paid to structural strength and resistance to loads, as shown by research by Gonabadi et al. [32]. Finite element models have optimized the blade design by considering the material properties of Glass Fiber Reinforced Polymer (GFRP) and the distribution of twist angles and chords along the blades. Another study showed that increasing the thickness of the blades near the roots can help overcome large structural loads without sacrificing hydrodynamic performance

[29,33]. The maximum placement of thickness along the chord is also vital to ensure constructive compatibility along the blades [34].

3.1.3 Surface roughness considerations

The rough blade surface can reduce aerodynamic performance by increasing drag and decreasing lift. Therefore, surface roughness considerations become essential in the design of ocean current turbine blades. Blades with hydrofoil shapes less sensitive to surface roughness can help maintain performance in polluted or mossy water conditions [35]. Several studies have shown that optimizing blade surfaces to reduce roughness can improve performance and resistance to erosion and cavitation [36]. Composite materials with a smooth, erosion-resistant surface layer have been proposed to increase blade longevity and reduce maintenance costs [37].

3.2 Material selection

Selecting the suitable material for the OCT blades is also very important. The material must withstand harsh ocean environments, including corrosion, biofouling, and high mechanical loads. In addition, the material must have sufficient strength and rigidity to ensure the stability and durability of the blade structure.

3.2.1 Structural strength and fatigue resistance

The selection of materials for ocean current turbine blades depends largely on structural strength and fatigue resistance. Composite materials such as Carbon Fiber Reinforced Polymer (CFRP) have become a top choice because they offer a high strength-to-weight ratio and good resistance to high load cycles [38]. Gonabadi et al. [30] They demonstrated that CFRP composites have significant tensile strength and can withstand cyclic loads experienced by ocean current turbine blades.

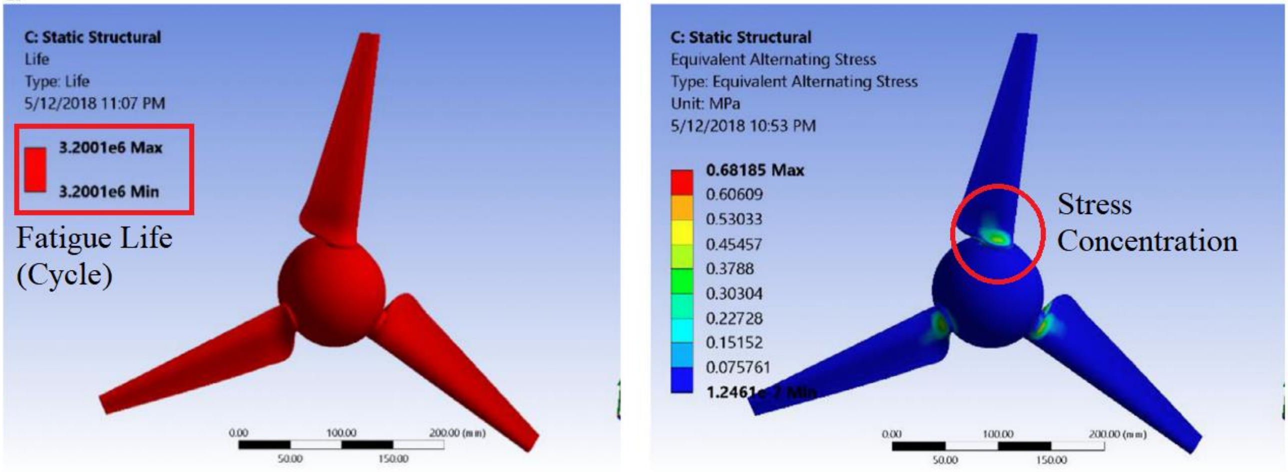


Figure 8. Finite Element Method (FEM) to investigate the fatigue strength of the blade design [40]

Finite Element Model (FEM) and Blade Element Momentum (BEM) theory have been used to optimize blade shape and predict the fatigue life of composite materials (see Figure 8). The use of FEM allows simulating stress distribution and deformation on turbine blades, while BEM is used to calculate the hydrodynamic force acting on the blades [39]. This combination of hydrodynamic and structural analysis was used in their study to design blades that could last more than 16 years under severe operating conditions [30].

3.2.2 Corrosion resistance and weight considerations

Corrosion resistance and weight considerations are other essential factors in the material selection of OCT blades. Composite materials generally offer good resistance to corrosive ocean environments. Gelcoat is often used as a protective layer on composite surfaces to protect against degradation due to seawater. However, these coatings can fail under high static and cyclic loads, so composite materials must be designed to withstand harsh environmental conditions [22].

Material weight is also an essential consideration in turbine blade design. The use of composite materials can reduce the overall weight of the blade, which in turn reduces the twisting and bending moments that the roots of the blade must withstand. This step is vital for improving the longevity and overall performance of the turbine. Despite their higher production costs, materials such as CFRP, which have lower density but higher strength than GFRP, are often chosen for this application [41]. Recent trends in material selection for OCT blades include using more advanced composite materials and innovative manufacturing methods. Additive manufacturing (3D printing) began to be applied to produce turbine blades with complex geometry and high accuracy. This method allows the creation of internal structures that can increase the strength and durability of the material without increasing weight. In addition, nanomaterials, such as nanocomposites and graphene, have been explored to improve mechanical properties and resistance to fatigue and corrosion. These nanomaterials can increase the strength of fiber-matrix interfaces in composites, reduce micro-cracks, and increase fatigue resistance [36,42].

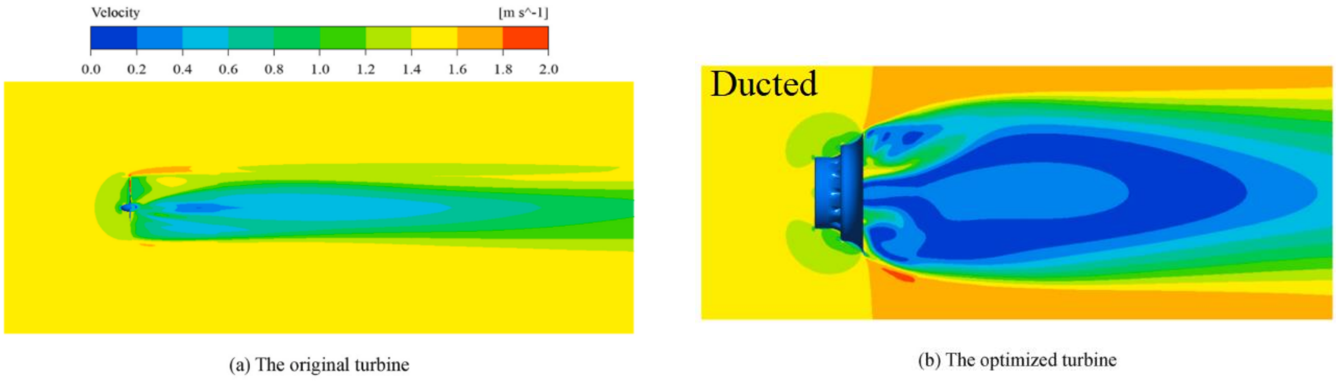
3.3 Hydrodynamic performance optimization

The hydrodynamic response of OCT blades to ocean currents needs to be carefully considered. This response includes forces acting on the blade, such as lift, drag, and twisting moment. Hydrodynamic response analysis helps in understanding blade performance and identifying potential design problems.

3.3.1 Numerical simulations and computational fluid dynamics

Numerical simulations and Computational Fluid Dynamics (CFD) have become critical tools in the ocean's design and performance analysis of current turbine blades (Figure 9). Blade Element Momentum (BEM) and CFD methods are widely used to predict hydrodynamic performance and blade structure. CFD enables more detailed fluid flow analysis by solving the Reynolds-Averted Navier-Stokes (RANS) equation or using the Large Eddy Simulation (LES) approach to capture complex turbulent phenomena [39,43].

The study by Lawson et al. [45] demonstrated that using CFD can provide accurate predictions of the hydrodynamic performance of Horizontal Axis Tidal Current Turbine (HATCT) and the resulting numerical data were validated experimentally. Harrison et al. [46] predicted that CFD will also be used to study the effect of ocean current turbulence on turbine performance. The CFD method provides geometric flexibility and the ability to simulate realistic onset velocity profiles and turbulence affecting fluctuating loads and blade fatigue [47].



(a) The original turbine

(b) The optimized turbine

Figure 9. Investigation of the interaction between fluid and structure as a basis for design optimization using the CFD method [44]

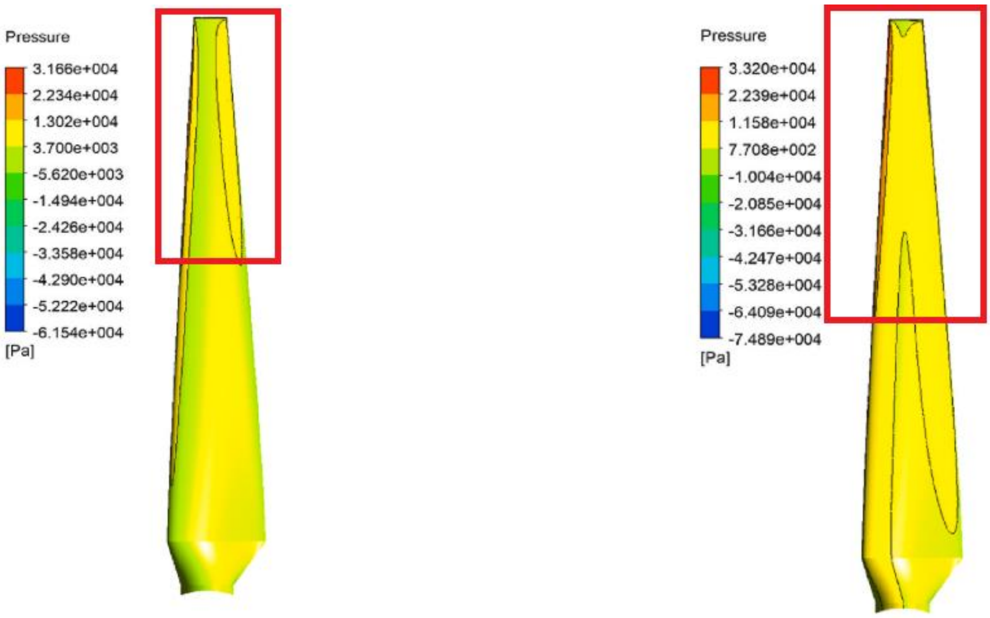


Figure 9. *Cont.*

3.3.2 Experimental testing and performance evaluation

Experimental testing is an essential step in validating ocean current turbine blade designs. These tests are carried out on various scales, ranging from small laboratories to field tests. Bahaj et al. [48] They used experimental testing to verify numerical predictions of the hydrodynamic performance of horizontal ocean current turbines. Experimental tests were also carried out to measure torque, power, and axial loads on turbines with various flow profiles, such as those by Allmark et al. [49].

3.3.3 Optimization techniques for blade design

Optimization techniques have been applied to improve efficiency and performance in turbine blade design. Genetic algorithms are examples of methods used to optimize the Shape of hydrofoils and the distribution of blade angles of attack [29]. Research by Nachtane et al. [41] used multi-point optimization to improve the performance of ocean current turbine hydrofoils, with results showing an increase in power coefficient of up to 50% at the optimal Tip Speed Ratio (TSR). A hybrid approach combining BEM and CFD has also been used to achieve a more optimal blade design. The study by Malki et al. [43] developed a modeling method that combines BEM with CFD flow domains to account for upstream hydrodynamic effects on rotor performance. Considering various operating conditions, this technique allows for a more accurate blade design.

4 Common Failures and Degradation Mechanisms of OCT Blades

Although OCTs offer great potential as a renewable energy source, the reliability and durability of the blades still need to be improved. OCT blades operate in harsh ocean environments and are exposed to various factors that can lead to failure and degradation. This sub-chapter will discuss common failures and mechanisms of blade degradation, focusing on four main factors, i.e., fatigue, erosion, cavitation, and harsh environments.

4.1 Fatigue

Material fatigue [50] is one of the leading causes of OCT blade failure. Cyclic loads resulting from fluctuations in the speed of ocean currents can cause microscopic cracks in the blades, which, over time, can develop into larger cracks and lead to structural failure. Careful blade design and proper material selection can help minimize fatigue risk.

Ocean current turbine blades must face cyclic loads and significant stress concentrations during operation. Constant cyclic loads can lead to material fatigue, becoming a primary degradation mechanism. These cyclic loads come from fluctuations in the speed of ocean currents, which generate fluctuating stresses on the blades. Gonabadi et al. [30] demonstrated that finite element analysis combined with BEM can predict stress distribution in ocean current turbine blades and identify critical zones prone to fatigue-induced failure. The use of FEA models allows simulation of the structural response of blades to cyclic loads, thus estimating the fatigue life of blades based on the S-N (Strain-Life) curve obtained from mechanical testing.

Research shows that fatigue failures in composite materials often begin with micro-cracks in the resin matrix, progressing to delamination and eventually leading to fiber failure [41]. Fatigue testing on composite materials uses a three-point fatigue testing rig (Three-Point Bending Rig) to replicate actual operating conditions at sea [45]. The fatigue data obtained from these tests are then used as input in fatigue damage accumulation models to predict the fatigue lifespan of blades. Fagan et al. [33] used a User Material (UMAT) subroutine-based approach in Abaqus software to implement a stress-based damage model on ocean current turbine blades. This approach allows the prediction of micro and macro damage to composite materials under cyclic loads.

4.2 Erosion

OCT blades are exposed to abrasion and erosion caused by solid particles suspended in ocean currents. Erosion can lead to thinning of the blades, loss of aerodynamic profile, and even structural damage. Abrasion-resistant blade materials and proper selection of coatings can help extend blade life and prevent erosion.

4.2.1 Abrasive wear due to sand and particle impingement

Ocean current turbine blades operate in highly abrasive environments, where sand particles and other particles carried by ocean currents can cause significant surface wear. This abrasive wear is one of the main degradation mechanisms affecting turbine blades' life and efficiency. Research shows that the impact of abrasive particles can lead to the initiation of damage to the material's surface, which then develops into more significant damage over time [41]. Studies show that particle impact on the blade's trailing edge can cause considerable damage to the resin matrix and composite fibers. They used numerical simulations to predict the stress distribution and deformation produced by particle impacts. The results showed that conic-shaped impactors produced maximum damage zones compared to hemispherical impactors [41,51]. In addition, the impact rate and particle geometry also significantly affect the wear and erosion rate of the blade surface [30].

4.2.2. Erosion-resistant materials and coatings

Researchers have focused on developing erosion-resistant materials and coatings to solve the wear and erosion issues. Composite materials such as Glass Fiber Reinforced Polymer (GFRP) and Carbon Fiber Reinforced Polymer (CFRP) are widely used due to their excellent mechanical properties and corrosion resistance. However, to increase erosion resistance, the material is often coated with a special coating designed to withstand the impact of abrasive particles [33].

Protective coatings based on nanomaterials, such as nanocomposites and graphene, have shown great potential in improving the erosion resistance of composite materials. Using nanocomposite coatings can enhance the strength of the fiber-matrix interface, reduce micro-cracks, and increase resistance to fatigue and erosion [52]. Bio composite-based erosion-resistant coatings can reduce the rate of erosion and extend the life of composite materials on ocean current turbine blades [53]. In addition, advanced manufacturing methods such as Vacuum Assistance Resin Transfer Molding (VARTM) for manufacturing composite blades have also shown positive results in improving mechanical properties and erosion resistance.

4.3 Cavitation

Cavitation occurs when the water pressure around the OCT blades drops below the pressure of water vapor, causing the formation of air bubbles [54]. These bubbles then implosively collapse, generating high pressure that can damage the blade surface. Cavitation can cause surface damage, erosion, and even excessive blade vibration. A blade design that minimizes cavitation formation and selects cavitation-resistant materials is essential to prevent cavitation-induced damage.

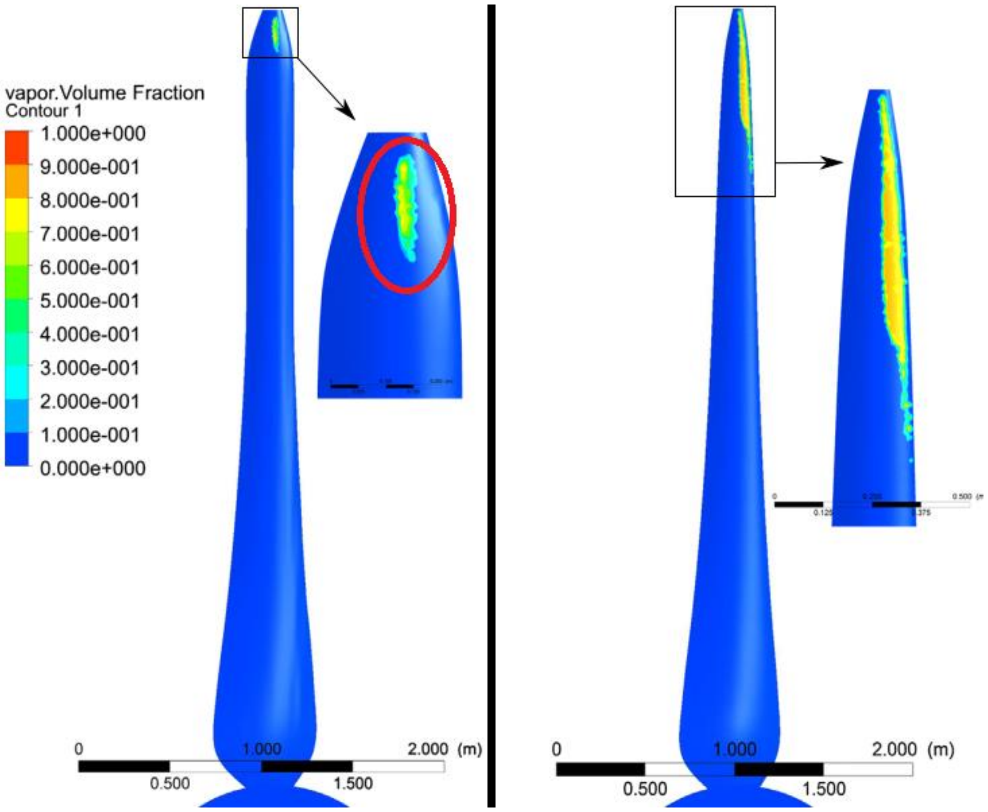


Figure 10. Cavitation phenomena in rotor blade [32]

Several studies [32,55] have used the BEM-FEM method to model the structural response of turbine blades to cavitation conditions (shown in Figure 10). They found that passive adaptive blades can delay the onset of cavitation and reduce the cavitation volume on the blade surface, allowing for smoother operation and reduced exposure to oscillations that cause fatigue. The study shows that the high-frequency excitation caused by cavitation can increase the fatigue rate in the system, which could lead to unexpected failures if cavitation analysis does not become an integral part of the design process.

Cavitation not only causes mechanical damage but also increases the drag coefficient, which reduces the blade hydrofoil's efficiency and increases the system's load [30]. Wimshurst et al. [56] emphasized the importance of hydrodynamic safety margins in cavitation analysis. They showed that conditions of ambient turbulence, free surface waves, and velocity shear can cause irregular pressure fluctuations that trigger the onset of cavitation, even if the minimum static pressure is above the water vapor pressure under stable flow conditions. This analysis highlights the need to increase the margin of safety to prevent cavitation at specific sites of turbine operation.

4.4 Impact loading with ocean creature

Ocean current turbine blades often operate in environments full of various sea creatures. The direct impact of ocean animals, such as large fish, mammals, and sea turtles, on turbine blades is one significant failure mechanism. Research shows that collisions between sea creatures and turbine blades can cause physical damage to the blades and the animal. The study by Hammar et al. [57] indicates that the collision probability between large fish and turbine blades is relatively high, especially at night when fish activity is more intense. The results showed that small fish tend to have the ability to avoid collisions with turbine blades, but large fish, such as sharks and stingrays, have a higher risk of being hit by turbine blades due to their lower evasion ability [58]. Damage from these collisions can include laceration, abrasion, contusion on sea creatures, and structural damage to turbine blades.

4.5 Harsh environment

OCT blades operate in extreme ocean environments, where they are exposed to corrosive salt water, ultraviolet light, and fouling of aquatic organisms. These environmental factors can accelerate the degradation of blade material and lead to structural failure. The selection of materials that resist corrosion and fouling, as well as proper surface treatment of the blades, can extend the service life of the blades and prevent damage from harsh environments.

4.5.1 The corrosion due to seawater exposure

Corrosion due to exposure to seawater is a significant problem affecting the longevity and performance of ocean current turbine blades. Seawater contains salts and minerals that can cause oxidation in blade materials, especially metal ones. It requires monitoring with non-destructive techniques such as ultrasonic testing to monitor corrosion levels and estimate the remaining life of turbine blade material [59].

4.5.2 The biofouling and ocean growth

The growth of ocean organisms on the surface of turbine blades, or biofouling, is another significant problem. Biofouling can lead to increased drag, decreased hydrodynamic efficiency, and increased structural load on turbine blades. Research shows that biofouling can reduce turbine blade performance by up to 30%. Using composite materials with anti-fouling coatings can reduce ocean organisms' growth rate on the turbine blades' surface [60]. These coatings prevent ocean organisms' adhesion to the blade surface, thereby maintaining hydrodynamic efficiency and reducing the need for routine maintenance. In addition, online monitoring technology has been proposed to detect and manage biofouling more effectively.

5 Challenges in the Development and Deployment of OCTs

There are at least three main challenges in developing and applying OCTs: durability and economic viability, environmental compatibility, and impact assessment. Effectively addressing both challenges is vital to realizing OCT's full potential as a sustainable and environmentally friendly renewable energy source.

5.1 Blade durability-economic viability

The durability and fatigue life of blades are essential factors in determining the economy and reliability of OCTs. The main challenge in this aspect was developing blades that are resistant to fatigue, erosion, cavitation, and fouling and are capable of operating for long periods with minimal downtime and maintenance costs. The initial investment cost for OCTs is still relatively high compared to other renewable energy sources, such as wind and solar energy. The challenge in this aspect is to develop more cost-effective technologies, including more efficient blade designs, cheaper materials, and more optimal manufacturing processes. Manufacturing technology and blade design innovations have helped reduce production costs and improve energy capture efficiency. Numerical optimization techniques and hydrodynamic simulations, such as CFD, allow for a more efficient and durable blade design [45]. In addition, integrating advanced technologies such as adaptive control and real-time monitoring can improve operational efficiency and reduce downtime due to breakdowns or maintenance.

5.2 Environmental compatibility and impact assessment

OCTs can have potential environmental impacts, such as interactions with ocean life, underwater noise, and changes in sediment flow. The challenge in this aspect is to conduct a comprehensive environmental impact assessment and develop mitigation strategies to minimize negative impacts on the ocean environment. It is crucial to ensure that OCTs are operated sustainably and responsibly, considering the balance between energy benefits and the sustainability of the ocean environment [56]. Mitigation methods such as eco-friendly design and careful operation arrangements can help reduce negative impacts on ocean ecosystems. Ecological compatibility and avoidance of damage to aquatic life are significant challenges in developing OCTs.

6 Concluding Remark

Ocean Current Turbines (OCTs) present promising opportunities to harness renewable energy from ocean currents, offering consistent and predictable power generation. This article has reviewed advances and challenges in OCT blade design, focusing on blade geometry, material selection, and hydrodynamic performance. Innovations in materials science, computational modeling, and experimental testing have significantly improved the efficiency and durability of blades. However, some challenges still exist, including resistance to fatigue, erosion, cavitation, and environmental impacts. To maximize the potential of OCTs, the technical challenges associated with this must be resolved through ongoing research and development. Improved materials, optimized design, and advanced manufacturing techniques can improve the performance and longevity of the blades. In addition, comprehensive environmental impact assessments and mitigation strategies are required to ensure the sustainable implementation of OCTs. Future research should prioritize integrating adaptive control technology and real-time monitoring systems to optimize operations and reduce maintenance costs. By overcoming these barriers, OCTs can be essential in reducing dependence on fossil fuels and contributing to global renewable energy goals, ensuring a cleaner and more sustainable energy future.

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