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Performance Study of a Humpback Whale Fluke Turbine on Foil Shape Variation Based on Double Multiple Streamtube Model

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Abstract

Exploration of ocean current energy allows for the development of turbines as the primary conversion device. Turbine technologies have been developed in various types, including bio-inspired turbines, such as the humpback whale fluke turbine. In this study, the achievement of a humpback whale fluke turbine is investigated by applying various forms of foil, both symmetric and asymmetric, to obtain the appropriate foil profile. Symmetric foils were represented by NACA 0012, NACA 0018, and NACA 0021, while asymmetric foils were represented by NACA 4312, NACA 4512, and NACA 4712 foils. Simulations were performed using QBlade software, which was developed based on the DMST theory. In general, symmetric foils have a more stable performance than asymmetric foils because they produce a better performance at positive and negative angles of attack. This result is also supported by a review of efficiency and self-starting capability where symmetric foils have significantly higher C_P values and positive C_Q along the azimuth angle than asymmetric foils. Finally, NACA 0021 foil is recommended for a humpback whale fluke turbine based on its efficiency and self-starting capability.

1. Introduction

Since the energy crisis in the early 1970s, the idea of harnessing renewable energy has gained more attraction. This breakthrough is fueled by the need to reduce reliance on fossil fuels, which have harmful environmental effects like pollution and greenhouse gas emissions [1]. Renewable alternatives like solar, wind, geothermal, and hydroelectric power have been continuously advancing. However, ocean energy such as tidal energy, wave energy, and ocean thermal has gained significant attention, especially in a country like Indonesia with its extensive coastlines. Tidal energy is particularly promising due to Indonesia's numerous potential straits formed by its archipelagic geography. Furthermore, the investment cost for tidal energy is the most beneficial among other ocean energy sources. From a technical standpoint, ocean energy mostly uses turbines that are readily implementable and widely used commercially [2].

Broadly speaking, based on their rotational axis orientation, tidal turbines can be categorized into horizontal axis current turbines (HACT) and vertical axis current turbines (VACT). Recently, extensive research has been conducted on VACT due to its many benefits, such as a uncomplicated design, easier fabrication process, low production cost, the ability to convert ocean currents from all directions, good performance under turbulent conditions, and electrical components can be placed on the surface [2, 3, 4, 5]. However, VACT has drawbacks in terms of low efficiency [7] and challenge in self-starting [8]. Based on their performance, VACT can be divided into Savonius turbines, which utilize drag force, and Darrieus-type turbines, which utilize lift force [9, 10]. However, as the technology advances, VACT is also designed based on inspiration from living organisms, known as bio-inspired turbines. One of the interesting bio-inspired turbines studied is the turbine inspired by the tail or caudal fin of a humpback whale, called fluke. This inspiration was developed from observing the agile movement of humpback whales despite their large and rigid bodies.

Several studies have been conducted on the humpback whale fluke turbine with varying names. Specifically, this turbine is a development of the Darrieus turbine that emphasizes a higher coefficient of lift performance. Initially, this turbine was introduced as the Achard-Maitre turbine. In subsequent developments, it was further developed with the name trapezoidal-shaped blade turbine, also known as the Zanette turbine [11]. This turbine uses NACA 0018 foil and has a solidity of 1.1. In terms of performance, this turbine produces good self-starting capability with an efficiency of 0.32. Adopting Zanette turbine in their research, [12] was conducted experimental investigation of this turbine in a small canal. By applying NACA 0020 as the base foil, this experiment was explored the effect of blade sweep angle variations of 15°, 30°, and 45°. The results exhibited that the 45° blade sweep angle variations yielded the highest efficiency at 0.1924, although the difference compared to the 30° angle was not statistically significant. In [13], a similar turbine called the delta-shaped blade turbine was studied. NACA 0020 foil and a solidity of 0.22 were considered in this study. The turbine produced excellent self-starting capability and efficiency at the right blade sweep angle of 30°. A fairly high efficiency of the humpback whale fluke turbine was achieved by [14]. In this study, the analyzed turbine was named the V-shaped blade, and its performance resulted in an efficiency of 0.375. They recommend a profile distance of "V" shape that is 0.6 times of the foil chord length. Geometrically, this turbine uses NACA 0021 foil and has a solidity of 0.25. In [15], several unique blade shapes was compared, one of which was the humpback whale fluke turbine inpired called arrow-shaped blade turbine. The geometric aspect of this turbine uses NACA 63_4021 foil and has a solidity of 0.43. This turbine can achieve the highest efficiency and shows better self-starting performance than all the other tested turbine shapes.

In summary, the research mentioned earlier reveals that the humpback whale fluke turbine has varying performance depending on the foil and dimensions used. The foil, which is essentially a geometric shape to improve the coefficient of lift, plays a critical role in determining the overall performance of the humpback whale fluke turbine. This turbine is an upgraded version of the Darrieus turbine, and the choice of foil greatly influences its overall effectiveness. Because the foil is so crucial, it's interesting and important to test the humpback whale fluke turbine using different foil types. This exploration will be beneficial in gaining a better understanding of how different foils affect the turbine's efficiency and performance. The investigation into foil design often involves discussions regarding the airfoil shape, with particular attention given to the profile thickness or camber [16], [17]. Therefore, various profiles, including symmetric foils like NACA00XX with different thicknesses or camber size, as well as asymmetric foils, play a part in determining the overall turbine performance.

To evaluate the performance of the VACT, various numerical models have been developed. The theoretical modelling of VACT performance is known to be quite complicated. Given the many problems that arise when designing VACT, a method called Double Multiple Streamtube (DMST) was introduced by Ion Paraschivoiu. In this method, two parameters are adopted on the circular path related to the blade and the energy extraction upstream and downstream [18]. This method has also been widely applied in many open-source software because of its fast modeling and easy analysis features [19]. A rapid estimation along with good simulation results makes this approach very reliable in analyzing turbine performance, especially in reducing the simulation cost and working time [20].

Therefore, the primary purpose of this research is to examine the performance of the humpback whale fluke turbine, especially concerning its efficiency and self-starting capability. Various types of foils will be applied to obtain better designs. By applying them to the same turbine geometry, the effect of foil performance on turbine efficiency can be more easily determined. For this purpose, DMST-based simulations will be used to obtain an overview of turbine performance, specifically in the preliminary study analysis stage. The implementation of DMST-based simulations can be conducted using an open-source software namely QBlade which exhibits numerous merits for preliminary turbine design.

2. Methods

2.1. VACT Numerical Considering Based on DMS

The Double Multiple Streamtube (DMST) model is developed as a combination of the Multiple Streamtube and Double Actuator Disk theories. Initially introduced by Ion Paraschivoiu, the Multiple Streamtube theory is used to predict flow by considering the momentum balance of each streamtube, which allows for variations in velocity perpendicular to the free stream direction. However, this theory's drawback is the inability to analyze the upstream and downstream regions separately. Hence, the Double Actuator Disk theory is proposed, assuming that two actuator disks are placed in a row connected to the turbine center. A detailed representation of the DMST theory is shown through illustrations in Figure 1.

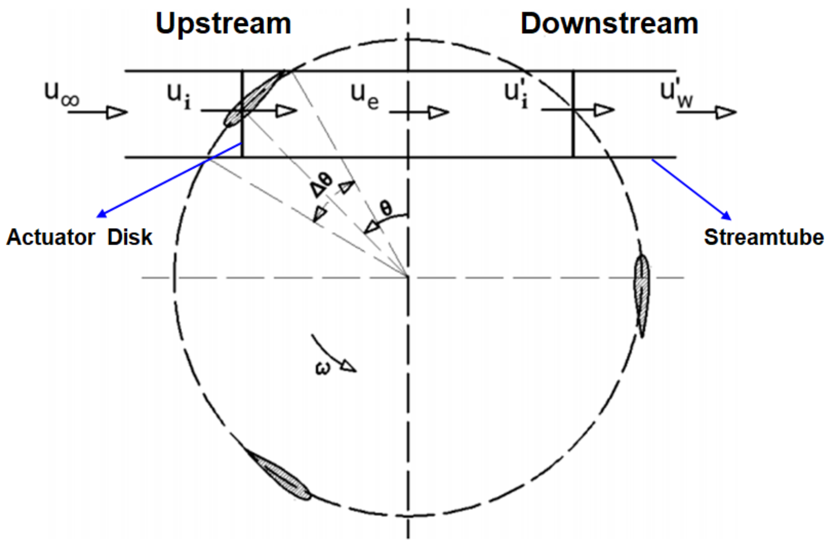


Figure 1. 2D schematic of the DMST model

DMST assumes that the inflow to the front blades has a velocity of U_i, while the induced velocity at the rear blades is U_i'. The variables U_∞, U_e, and U_w' represent the free stream velocity, the flow velocity at the turbine center, and the flow velocity after the rotor, respectively. The induced velocity can be formulated as follows:

$$U_i = \frac{U_\infty + U_e}{2} \tag{1}$$

$$U_i' = \frac{U_e + U_w'}{2} \tag{2}$$

The relative velocity vector (w), as the primary velocity vector responsible for turbine performance, is a function of the turbine's angular velocity and induced velocity. Thus, two different relative velocity functions can be written for the upstream and downstream sections of the rotor, respectively:

$$w = \sqrt{[(U_i \sin\theta)^2 + U_i \cos\theta + \omega R^2]^2} \tag{3}$$

$$w' = \sqrt{[(U_i' \sin\theta)^2 + U_i' \cos\theta + \omega R^2]^2} \tag{4}$$

Finally, the thrust, torque, and power coefficients that are solved for w and w' separately can be represented as follows:

$$C_T = \frac{2}{\pi}\left(\frac{Bc}{2R}\right)\left(\frac{w}{U_\infty}\right)^2\left(C_t\frac{\cos\theta}{\sin\theta} - C_n\right) \tag{5}$$

$$C_Q = \left(\frac{Bc}{2R}\right)\sum_{i=1}^{N_\theta}\frac{\left(\frac{w}{U_\infty}\right)^2 C_t}{N_\theta} \tag{6}$$

$$C_P = C_Q\lambda \tag{7}$$

$$\lambda = \frac{\omega R}{U_\infty} \tag{8}$$

where C_T is the thrust coefficient, B is the number of blades, R is the rotor radius, C_t is the tangential force coefficient, C_n is the normal force coefficient, C_Q is the torque coefficient, λ is the tip speed ratio, and ω is the turbine angular velocity.

2.2. Foil Shape Consideration

The selection of appropriate foil shapes is a critical parameter in maximizing turbine efficiency [21]. In this section, various foils commonly used in Darrieus turbines will be compared for their application in a humpback whale fluke turbine. Generally, these foils can be categorized into symmetric and asymmetric foils. For symmetric foils, NACA 0012, NACA 0018, and NACA 0021 are chosen, which are frequently used in vertical-axis turbine designs because they function to minimize negative torque during single rotor rotation. Several studies have demonstrated the advantages of each of these foils. In [22], the demonstration of the NACA 0012 foil produced good achievement in terms of force, velocity, and lift coefficient compared to the other three comparative foils. The superiority of NACA 0012 was also confirmed in [23], which found that this foil can generate good lift force and high angular velocity. The NACA 0018 foil was found to be a good choice for Darrieus turbine design according to the study from [24]. This is because NACA 0018 produces the finest aerodynamic performance over most of the tip speed ratio range, especially when compared to symmetric foils ranging from NACA 0012 to NACA 0021. The superiority of the NACA 0018 foil for Darrieus turbines was also reported in [25]. On the other hand, the NACA 0021 foil is applied for the V-blade turbine case [14]. This foil also provided the best efficiency compared to both symmetric and asymmetric foils such as S1046, FXLV152, and S809 as stated in [26].

As for the asymmetric foils, NACA 4312, NACA 4512, and NACA 4712 are chosen. Asymmetric foils have camber to increase lift force at zero angle of attack and function at higher maximum torque. Asymmetric foils also provide higher turbine efficiency along λ than symmetric foils. In [27] the rotor performance was investigated with asymmetric foils NACA 4512 and NACA 7512. The result showed that the NACA 4512 airfoil had better performance, even when compared to symmetric foil NACA 0012. The study from [28] was demonstrated that NACA 4712 had the highest power coefficient compared to NACA 4312 and NACA 4512. Based on existing studies, symmetric and asymmetric foils have their respective advantages that need to be compared for the same turbine to achieve the best performance. Symmetric foils (including NACA 0012, NACA 0018, and NACA 0021) and asymmetric foils (including NACA 4312, NACA 4512, and NACA 4712) have profiles as illustrated in Figure 2.

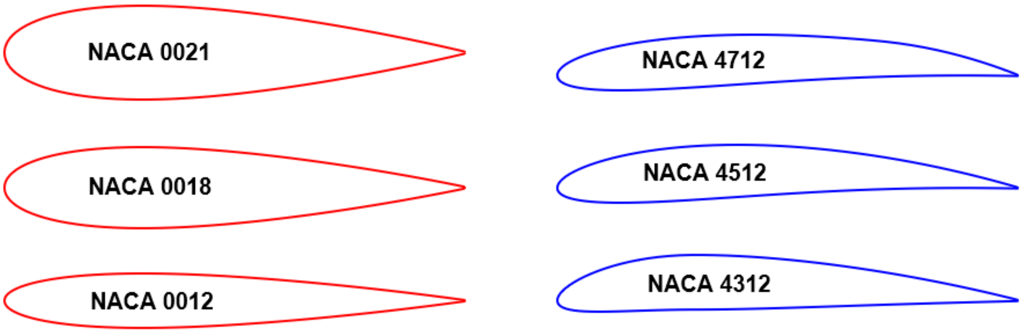


Figure 2. Geometry sketches of the selected symmetric (red) and asymmetric (blue) airfoils.

2.3. Turbine Geometry and Computational Processes

In this study, the turbine geometry was selected based on several considerations as follows:

- The use of three blades which are commonly used and provide good performance in VACT.
- The aspect ratio (AR) and solidity (σ) values refer to the basic Achard-Maitre turbine design, with values of 2 and 0.9, respectively, which have a turbine height of 1 m, turbine radius of 0.5 m, and chord length of 0.15 m.
- The extremities chord ratio (Λ) of 0.5 was used to obtain an upper chord of 0.1 m and a lower chord of 0.2 m [29].
- A leading sweep angle (γ) of 30° was applied, which showed the most optimal performance in [13].

According to the considerations above, the geometric properties of the turbine were determined as shown in Table 1, and its visualization is represented in Figure 3a and Figure 3b. For the Reynolds number considered, it can be calculated from the values of the variables, where the current velocity is determined to be 3.0 m/s and the kinematic viscosity of seawater is 1.189 x 10^{-6} m^2/s (at a temperature of 15°C and a salinity of 35 g/kg), resulting in the following calculation:

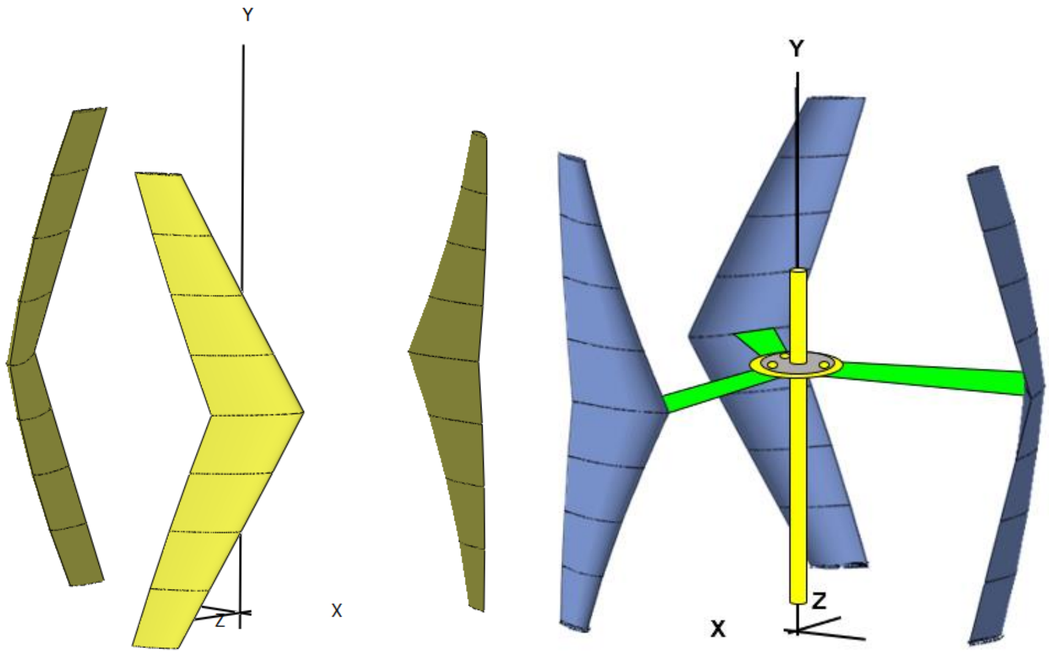
$$Re = \frac{U_\infty c_m}{\nu} = \frac{3 \times 0.15}{1.189 \times 10^{-6}} \approx 380.000$$

Table 1. The geometric properties of the turbine

Dimension	Notation	Value (m)
Foil	-	NACA 0012, 0018, 0021, 4312, 4512, and 4712
Number of blades	N	3
Turbine height	H	1.00 m
Turbine radius	R	0.50 m
Mean chord length	c_m	0.15 m
Upper chord length	c_u	0.10 m
Lower chord length	c_l	0.20 m
Solidity	σ	0.9
Aspect Ratio	AR	2
Extremeties chord ratio	Λ	0.5
Leading sweep angle	γ	30°

Furthermore, the computation process based on the DMST method in this study is assisted by the QBlade software, with the following steps:

1) Importing each foil with a .dat extension.
2) Simulating the foil with XFOIL direct analysis to obtain the lift coefficient (C_L), drag coefficient (C_D), and lift-to-drag ratio (C_L/C_D).
3) Extrapolating C_L and C_D at AoA 360° using the Montgomerrie-Viterna method.
4) Designing the physical parameters of the predetermined turbine.
5) Simulating the turbine rotor with the DMST code to obtain the power coefficient (C_P) as a representation of turbine efficiency and the turbine torque coefficient (C_Q) as a representation of the self-starting capability of the turbine.
6) Simulating the turbine power production.



(a) (b)

Figure 3. Visualization of humpback whale fluke turbine (a) in QBlade (b) for Implementation

3. Results and Discussion

3.1. Double Multiple Streamtube Validation

The QBlade algorithm has been validated against the experimental data of the 17-m Sandia turbine and the numerical output of DMST theory. The results are highly satisfactory, as shown in Figure 4. The QBlade code exhibits behavior very similar to the numerical DMST code initially proposed by Paraschivoiu, though only up to the peak power. Beyond this point, the QBlade simulation output tends to be constant, indicating the occurrence of turbine power cut-off. The high accuracy of QBlade is particularly evident when compared to the experimental data, as the power values are close from the initial point to the determined cut-off point. However, it should be noted that QBlade shows slightly higher results than the two reference data, with a difference that is still tolerable. Overall, the QBlade algorithm validated against the 17-m Sandia turbine is effective and provides good agreement with experimental results, as demonstrated in [30].

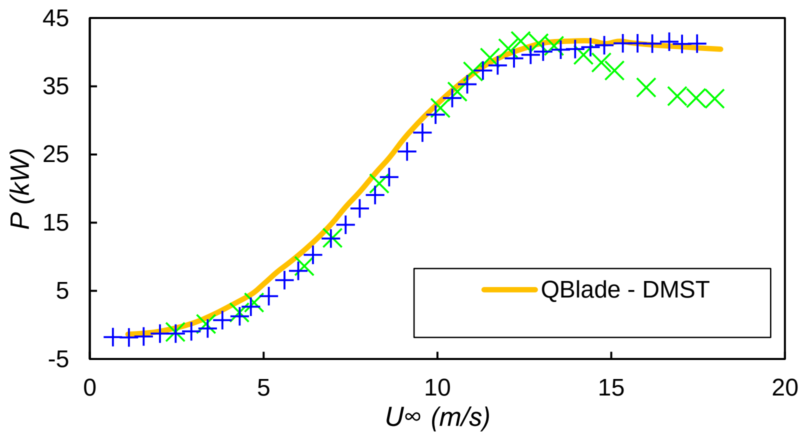
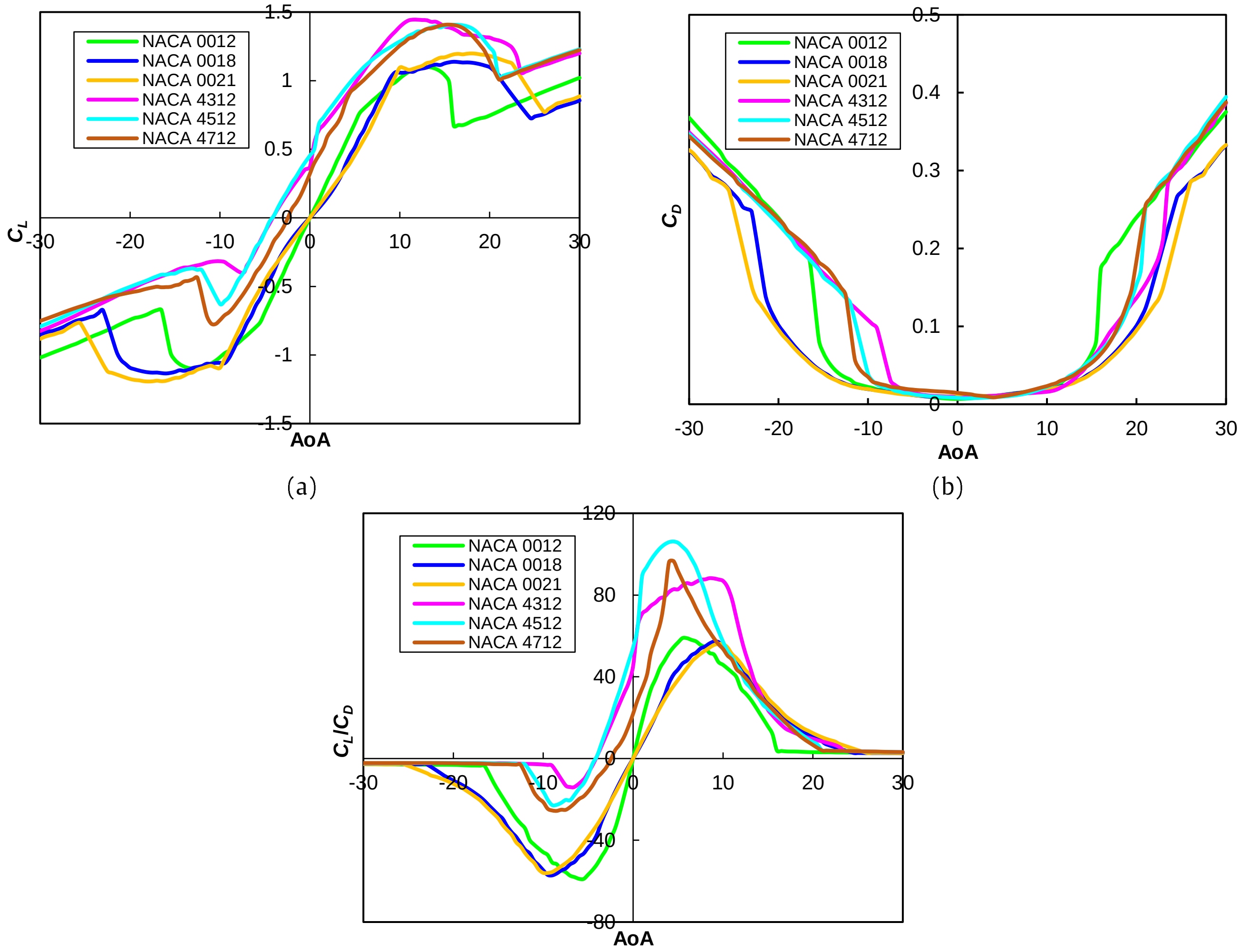


Figure 4. Validation of QBlade algorithm code

3.2. Comparison of Foil Performance

The performance of a foil can be evaluated based on its lift coefficient (C_L), drag coefficient (C_D), and lift-to-drag ratio (C_L/C_D), as shown in Figure 5. From the comparison of C_L in Figure 5a, it is obvious that the asymmetric foil has a higher C_L value as opposed to the symmetric foil, especially in the positive angle of attack (AoA) range. Meanwhile, the C_D value tends to be similar for all foils, especially in the AoA range of -5° to 15°, as shown by the curve in Figure 5b. This results in the lift-to-drag ratio of the asymmetric foil being much higher than the symmetric foil, as shown in Figure 5c. This finding is also supported by other studies such as in [31], which found that at nearly identical Reynolds numbers of 330,000, the asymmetric foil performed better than the symmetric foil. The same conclusion was also reported in [32], who found that the lift-to-drag ratio of the asymmetric foil is greater than that of the symmetric foil. However, the good performance of the asymmetric foil only occurs at positive AoA, as at negative AoA, the asymmetric foil has worse performance than the symmetric foil. This phenomenon is also reported in other studies, such as in [33]. Upon closer examination, the performance of the symmetric foil tends to be stable both at positive and negative AoA, making it a more widely developed basis for foils in Darrieus turbines or other vertical-axis turbines.

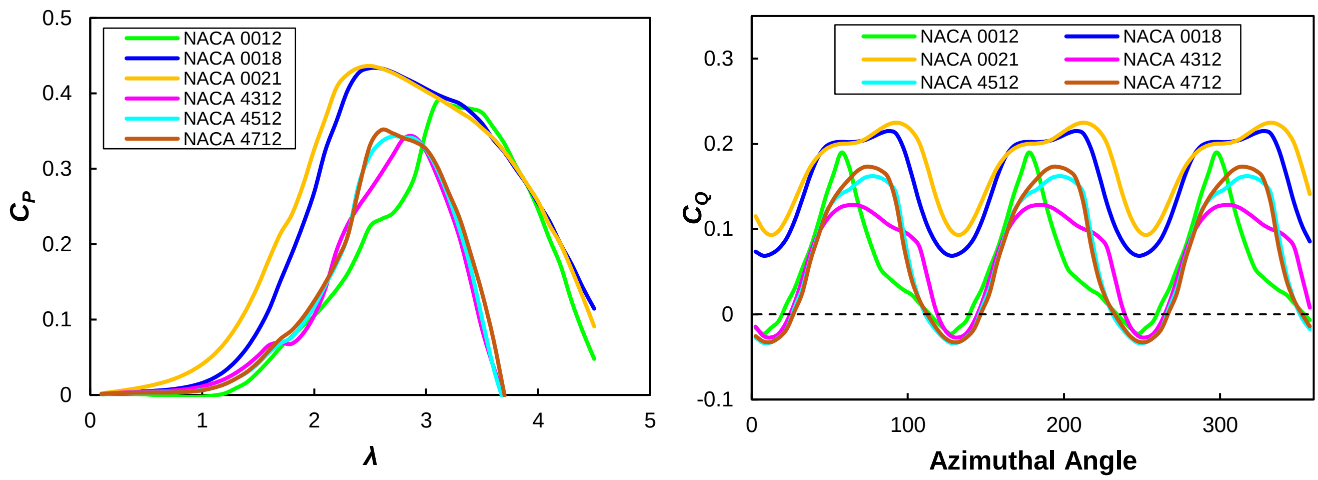
In general, the C_L value increases progressively at low AoA until it stalls at high AoA. This is because the laminar fluid flow experienced by the foil at low AoA, in which the flow velocity on the outer part is faster than that on the inner part. This velocity difference results in a lift force that can pull the foil forward. If the lift force increases to a certain point, then eventually it will reach a point where the flow becomes turbulent, causing the lift force to disappear [34]. This phenomenon is often referred to as a stall, which is marked by a sudden drop in the C_L value at high AoA.



(a) (b)

(c)

Figure 5. Coefficient comparison from all tested (a) C_L (b) C_D and (c) C_L/C_D



(a) (b)

Figure 6. Performance comparison of all applied foils for humpback whale fluke turbine: (a) C_P and (b) C_Q

3.3. Analysis of Efficiency and Self-Starting Capability

After obtaining the performance of each foil, the foils were applied in a turbine model. The turbine model studied in this discussion is a humpback whale fluke turbine. With the same geometry, it is expected to determine which foil provides maximum performance for the turbine, especially relating to the efficiency and self-starting capability. For the evaluation of efficiency, the power coefficient (C_P) is an important variable in evaluating turbine efficiency. In this simulation, the tip loss variable is applied to obtain a more accurate efficiency measurement [35]. Tip loss often occurs in turbine blades, especially at the tip. The application of each foil to the humpback whale fluke turbine provides the turbine C_P value as shown in Figure 6a. It is apparent that even though the asymmetric foil has a high C_L/C_D at a positive AoA, it only produces lower turbine efficiency and a narrower operating range than the symmetric foil due to its poor C_L/C_D performance at negative AoA. The increasing difference in the maximum camber location between NACA 4312, NACA 4512, and NACA 4712 foils, which are represented by the second digit of the foil, only slightly shifts the maximum C_P value to smaller λ values. In general, the selected type of asymmetric foil does not show a significant difference between one and the other. However, it can be observed in detail that the highest C_P value and wider operating performance range of the asymmetric foil are achieved by the NACA 4712, NACA 4512, and NACA 4312 foils, respectively, as reported in [28]. This indicates that adding camber positions can slightly increase turbine efficiency.

The best turbine efficiency is achieved with the use of a symmetric foil. Adding thickness, represented by the last two digits of the foil, can significantly increase turbine efficiency. For NACA 0012, the obtained C_P value is only 0.39, while NACA 0018 and NACA 0021 can produce C_P values of 0.433 and 0.436, respectively, at the same λ value. This result also indicates that, when applied to the humpback whale fluke turbine, adding foil thickness greater than 21% chord length (such as in NACA 0021) does not have a significant impact on efficiency improvement. The performance of NACA 0021 only slightly has a wider operating range than NACA 0018. However, adding foil thickness will certainly increase the radius of curvature at the leading edge. This can allow for lighter pressure changes bringing about better stall characteristics. This phenomenon is clearly evidenced by experimental and numerical results since the power coefficient of NACA 0021 is greater than NACA 0018 for all λ values. Nonetheless, thinner foils also have other advantages because they tend to have better performance for turbines with low solidity at high tip speed ratios.

The next evaluation was conducted by examining the value of the torque coefficient (C_Q) at a certain λ as shown in Figure 6b. In this case, λ = 2.1 was chosen, referring to the research from [36], which states that the Darrieus turbine does not have self-starting capability at $0 \leq \lambda \leq 2$. The C_Q values of all foils applied to the humpback whale fluke turbine are shown in Figure 5b. It is clear that the symmetric NACA 0018 and NACA 0021 foils have good self-starting capability as they are able to generate positive C_Q values along the azimuth angle. Based on their average values, NACA 0021 is recommended because it has a 13.11% larger C_Q value compared to NACA 0018. The good self-starting capability of the NACA 0021 foil is also found in [37]. Meanwhile, the assertion that a thicker foil will result in better self-starting capability, as revealed in [38], is also confirmed by the same foil profile. The research shows that NACA 0021 has better self-starting performance compared to NACA 0018 and NACA 0012 foils.

In summary, the NACA 0021 foil can be recommended as the primary foil for a whale fluke turbine, considering its superiority in efficiency and self-starting. In addition to these advantages, the thickness of the NACA 0021 foil also beneficial in strengthening the blade structure, which may experience fatigue due to fluctuating forces during a full rotation of the turbine. However, further investigation is needed, particularly regarding the findings of many studies that suggest an improvement of turbine power coefficient or efficiency can reduce the turbine's self-starting capability, and vice versa [39], which was not discussed in this study.

In the end, achieving high efficiency in a turbine is an important task. This is because the power that can be utilized will ultimately be the net power that has been reduced by electrical losses due to generators and power electronics components. Mechanical losses through the use of gear components can also decrease the turbine efficiency outside of its ability to extract power from water. In energy conversion applications that utilize mechanical components, the losses that arise can be caused by the use of bearings that result in "spelling behavior", mechanical friction, and nonlinear interactions of the gear system [40]. These losses can certainly be minimized through good system design and fabrication processes. Having self-starting capability is crucial as it eliminates the need for an external starting device. A turbine with good self-starting capability will rotate directly when fluid with a certain velocity hits it. If this is not achieved, an external starting device is required, which is usually generated electrically to drive the rotating motor. Unfortunately, this way can lead to disadvantage in the form of increased O&M costs and system complexity.

4. Conclusion

In conclusion, this study conducted research on the humpback whale fluke turbine, which has promising developments in its application as a tidal turbine. The DMST theory applied to evaluate the turbine's performance was well tested, as evidenced by the validation of this theory, which approximates its experimental value. Using the same geometry, several symmetric and asymmetric foil shapes were evaluated to obtain the proper foil for the humpback whale fluke turbine. Asymmetric foils were found to have good performance, but only in positive AoA areas, whereas symmetric foils were able to produce stable performance in both positive and negative AoA areas. Based on the efficiency analysis, it was found that symmetric foils have an advantage over asymmetric foils, where NACA 0018 and NACA 0021 foils were competitive in producing maximum C_P values. From the examination of self-starting capability, it became increasingly clear that symmetric foils, especially NACA 0021, were favored as the main foil for the humpback whale fluke turbine. The advantages of thicker foils that can strengthen the turbine structure and improve self-starting capabilities make NACA 0021 suitable for humpback whale fluke turbine applications. However, the relationship between efficiency and self-starting needs to be further investigated, given the many studies that have revealed the inverse relationship between these two parameters.

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