Innovation in Vertical Axis Hydrokinetic Turbine – Straight Blade Cascaded (VAHT-SBC) design and testing for low current speed power generation

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Abstract. This study examines an innovative turbine with the addition of the number and arrangement of straight blade cascaded (SBC). SBC is a combination of passive variable-pitch and fixed pitch of each turbine arm. This study was conducted in an open channel flow that has a current velocity (V-m/s) of 1.1, 1.2, and 1.3. RPM and torque were measured for coefficient of performance (Cp) and tip speed ratio (TSR) calculation. Without changing the turbine dimension, the employment of cascaded blade (three blades in each arm) contributes to improve energy extraction significantly. A significant increase in Cp value is seen when 9 blades (3 cascaded blades per arm) are used with a Cp 0.42 value at TSR 2.19. This value has reached 93% of the maximum theoretical Cp value.

Key words: vertical axis, hydrokinetic turbine, straight blade cascaded, passive variable pitch, fixed pitch, Cp

1. Introduction
Hydrokinetic turbines extract mechanical power from flowing water without dam. They operate essentially identical principles as wind turbines at low Froude numbers. Hydrokinetic turbines used for harnessing renewable energy sources such as rivers, drainage flows, tidal flows, and ocean currents [1]. The mechanical energy that has been generated from hydrokinetic turbine, then converted into electrical using a generator.

Straight-bladed or Darrieus turbines has number of blades that rotate around an axis that perpendicular to the flow. These turbines can receive flow from any direction, as long as the flow perpendicular to the axis of rotation. These turbines do not require yaw control [1]. Straight-bladed or Darrieus turbines is one type of Vertical Axis Hydrokinetic Turbine (VAHT).
VAHT should have high coefficient of performance (Cp) in order to extract current energy to mechanical energy as much as possible. Several methods to obtain optimal Cp have been developed by researchers. Aspects regarding these research are to optimize some design parameters VAHT such as, number of blades [2], height to radius ratio [3], type of airfoil [4], and solidity [5]. Theoretical model was used for the design and performance simulation of Darrieus-type vertical axis turbine, such as number of blades affects, coefficient of performance (Cp), and structural stability. As number of blades decreases, range of operating tip speed ratio increases. It should be noted there is no significant difference of Cp max when the turbines consist with one blade, two blades or three blades. The lower number of blades used, the wider Cp curve. Implementing one bladed turbine is not possible due to unbalanced centrifugal forces. Three bladed turbines gives more stability (Cp max = 0.1) than two bladed turbines. Generally, some research use 3 blades on VAHT [1] [3] [6] [7] [8].

Other design parameter is height to radius ratio (H/R). Newly developed vortex method was used for modelling three-dimensional effects vertical axis tidal current. The numerical results show that if the height is more than six times radius, the Cp max increases slower correspond to the turbine height. The Cp max reached more than 0.43 [3]. However, this study uses numerical study, not using experimental study.

Type of airfoil affects the value of Cp. Reference [4] investigated the effect of several airfoils toward Cp max by using Computational Fluid Dynamics (CFD). These airfoils were NACA 00XX, NACA 63XXX, S-series, A-series and FX-series. Airfoil S-1046 had highest Cp max among others. NACA 0018 had highest Cp max among other NACA series. As a note, turbines which consist of symmetrical airfoils have better performance than asymmetric airfoil turbines. As a note, turbines consisting of symmetrical airfoils have higher performance than asymmetric airfoil turbines. NACA 0018 is the best airfoil for NACA series and usually used for Darrieus turbines [4]. Furthermore, NACA 0018 has the best characteristics for VAHT. Due to the high value of thickness to chord ratio so that have enough power to withstand bending, NACA 0018 is usually used for Darrieus turbines. [6]. Thus, the airfoil with the highest max Cp is NACA 0018 (Cp max = 0.2964) and S-1046 (Cp max = 0.4051) [4].

Solidity is another parameter affecting the performance of turbines. Reference [5] investigated the effect of solidity towards Cp max by using numerical study. In this study, the solidity was varied of 0.3, 0.4, 0.5, and 0.6. This study confirmed that higher Cp max was obtained in lower solidity, highest Cp max is 0.43 obtained for solidity of 0.3. In addition, the field test was conducted for solidity of 0.84 and showed that Cp max was 0.25.

Cp higher than 0.4 obtained on [3] [4] [5]. However, these researches are numerical study. To validate numerical calculation results, experimental study was used. Experimental study also give support for the design of the prototype which is investigate three types of variable pitch VAHT. Considering the control rules, the turbine can classified as cycloid type controllable-pitch, spring-control variable-pitch, and passive variable-pitch vertical axis turbine. Between those control rules, highest Cp max is 0.33 obtained from spring-control variable-pitch [8].

Cp max or Cp peak, which can be achieved by Darrieus type VAHT is 0.45 in the theoretical value [9]. So that still needed further research, to get Cp max approaching the theoretical value. This experimental study proposes an innovative turbine with the addition of the number and arrangement of straight blade cascaded (SBC). SBC is a combination of variable passive pitch and fixed pitch of each turbine arm. This study was conducted in an open channel flow that has a current velocity (V·m/s) of 1.1, 1.2, and 1.3. RPM and torque were measured for coefficient of performance (Cp) and tip speed ratio (TSR) calculation. Considering the number of blade, the experiments can classified as VAHT 3 blades, VAHT-SBC 6 blades, and VAHT-SBC 9 blades.
2. Experimental Methods

2.1. VAHT-SBC Specifications

Fiberglass was used for blade materials, while shaft, turbine arm, and frame used steel as material. Width and depth of the open channel was used to determine the design parameter of the turbine. Table 1 shows design parameter that was used in this research.

The position of passive variable-pitch gives the freedom to move within the range -20° to 20°, as shown in figure 1 (a) & (b). There are airfoil plate on the top of variable pitch blade. The airfoil plate is used as a sacrifice that crash into the inner stopper and the outer stopper, as shown in figure 1 (c).

Passive variable-pitch located at turbine radius (R), while fixed pitch located at 0.75 R and 0.5 R. Considering the number of blade and the arrangement of blade, the experiments can classified as VAHT 3 blades, VAHT-SBC 6 blades, and VAHT-SBC 9 blades, as shown in figure 2. The VAHT 3 blades represents conventional turbines, while VAHT-SBC 6 blades and VAHT-SBC 9 blades represents the innovative turbines proposed in this study.

| Design Parameter         | Dimension       |
|--------------------------|-----------------|
| Turbine diameter (cm)    | 80              |
| Span of blade (cm)       | 80              |
| Number of arm            | 3               |
| Shaft diameter (cm)      | 3.2             |
| Airfoil of blade         | NACA 0018       |
| Length of chord (cm)     | 10              |
| Pitch angle range (°)    | -20 to 20       |
| The placement of blade 1 | R               |
| The placement of blade 2 | 0.75 R          |
| The placement of blade 3 | 0.5 R           |
| Frame dimension (cm)     | 90 x 90 x 134   |

Figure 1. (a) Fixed Pitch, (b) Passive Variable-Pitch and The Pitch Angle, (c) Stopper Mechanism
2.2. Test location
Experimental study conducted in an open channel flow. The current velocity was 1.1 m/s – 1.3 m/s. Width of the channel is 1 m and depth is 1.7 m, as shown in figure 3 (a). Width and depth of the open channel was used to determine the design of the turbine and the frame.

2.3. Experimental set-up
The current velocity data collection was carried out at 3 locations by using the current meter of Dentan CM-1BX series, as shown in figure 4. Propellers of the current meter are placed in 0.5 m from the turbine frame, collected by 10 data. The data were processed to obtain an average value. Average current velocity in 3 locations can be seen in table 2.
Table 2. Current Velocity at 3 Different Location

| Location | Average of current velocity (m/s) |
|----------|----------------------------------|
| Location 1 | 1.1 m/s                          |
| Location 2 | 1.2 m/s                          |
| Location 3 | 1.3 m/s                          |

Turbine torque data on azimuth (Θ) 0°, 90°, 120°, 180°, and 240° were taken using the JTN 4603BN series torque wrench. Torque wrench was used by locking the tip of the torque wrench to the tip of the turbine shaft, as shown in figure 5. Each azimuth performed 10 torque data retrieval, thus for one model turbine and one variation of current velocity obtained a total of 50 torque data. The data were processed to obtain average torque for 3 model turbines and for 3 variations of current velocity.

The RPM data (rotation per minute) of the turbine were taken using the ONOSOKKI HT-3200 series tachometer. The tachometer was used by locking the end of the tachometer to the tip of the turbine shaft, as shown in figure 6. For one variation of current velocity and one model turbine, RPM data were taken as many as 10 data. The data were processed to obtain an average RPM for 3 model turbines and for 3 variations of current velocity.
3. Results and Discussion

Turbine performances can be presented in the form of $C_p$. $C_p$ shows the amount of mechanical power that can be extracted from current power by the turbine. The larger the $C_p$, the greater the power that can be extracted by the turbine. $C_p$ is a powerful variable to compare the performance of a turbine. $C_p$ is expressed in equation (1) [10]. Where $\tau$ is torque (N.m), $\omega$ is angular velocity (rad/s), $\rho$ is water density (kg/m$^3$), $A$ is swept area of the turbine (m$^2$), and $V$ is current velocity (m/s).

\[
C_p = \frac{\tau \omega}{0.5 \rho A V^2}
\]  

(1)

Tip Speed Ratio is the ratio between the tangential velocity of the blade and current velocity. The TSR value states how fast the turbine is spinning against a certain current velocity. TSR is expressed in equation (2) [10]. Where $R$ is turbine radius (m), $\omega$ is angular velocity (rad/s), and $V$ is current velocity (m/s).

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TSR = \frac{R \omega}{V}
\]  

(2)

![Figure 7. RPM-Current Velocity Curves for Three Model Turbines](image)

Based on figure 7, the relationship between RPM and current velocity is proportional. The higher the current velocity, the higher the turbine RPM. VAHT 3 blades has the highest RPM on the three variations of current velocity, followed by VAHT-SBC 6 blades, then 9 blades. The highest RPM of 68.4 rpm is obtained at a current velocity of 1.3 m/s by VAHT 3 blades. The increase of current velocity has a positive effect on RPM, while the addition of blades has negative effect on RPM.

Moment inertia consists of mass (kg) and radius (m) variable. VAHT 3 blades, VAHT-SBC 6 blades, and VAHT-SBC 9 blades have the same radius. The variables that distinguish between the turbines is the mass. The turbine mass will increase as the number of blades increases. VAHT-SBC 9 blades has a higher mass and a higher moment inertia than VAHT-SBC 6 blades and VAHT 3 blades, respectively. Thus, VAHT-SBC 9 blades has the lowest RPM among the three other turbine variations, because it has the highest moment inertia.
Figure 8. Torque-Current Velocity Curves for Three Model Turbines

Based on figure 8, the relation between current velocity and turbine torque is proportional. The higher the current velocity, the higher the turbine torque. VAHT-SBC 9 blades has the highest torque on all variations of current velocity followed by VAHT-SBC 6 blades and VAHT 3 blades. Increasing the number of blades and current velocity has a positive effect on the torque of VAHT-SBC 6 blades and VAHT-SBC 9 blades.

VAHT-SBC 9 blades has the highest torque between VAHT-SBC 6 blades and VAHT 3 blades for three variations of current velocity. VAHT-SBC 9 blades has a higher moment inertia than VAHT-SBC 6 blades and VAHT 3 blades. The turbine mass will increase as the number of blades increases. The increasing in mass will increase the turbine moment inertia and the torque.

The darrieus type VAHT in this study is a lift device, a turbine that utilizes a lift force from a blade to rotate. The addition of a blade causes an increase in the lift force acting on the turbine. VAHT-SBC 9 blades has more blade, so it gives the largest lift force and also the largest torque than VAHT-SBC 6 blades and VAHT 3 blades. It is because the higher the lift force, the higher the turbine torque. Through the innovation of SBC mechanism, VAHT torque increased without increasing the dimensions of the turbine.

Figure 9. Cp - TSR Curves for Three Model Turbines
Based on the current velocity data, torque and RPM, the value of Cp and TSR can be obtained using the equations (1) and the equation (2). Figure 9 shows the graph of the relationship between TSR and Cp. The highest Cp was produced by VAHT-SBC 9 blades, followed by VAHT-SBC 6 blades and VAHT 3 blades. The highest Cp is 0.42 obtained on TSR 2.19 by VAHT-SBC 9 blades. The Cp value of 0.42 has reached 93% of the maximum theoretical Cp value. While the lowest Cp is 0.18 obtained on TSR 2.2 by VAHT 3 blades. The addition of the number and arrangement of straight blade cascaded has positive effect on Cp of the VAHT-SBC 6 blades and VAHT-SBC 9 blades.

4. Conclusions
In this study, an experimental study was conducted on an open channel to investigate an innovative turbine with the addition of the number and arrangement of straight blade cascaded (SBC). Average torque and average RPM of 3 model turbines (VAHT 3 blades, VAHT-SBC 6 blades, and VAHT-SBC 9 blades) on 3 variations of current velocity were measured for coefficient of performance (Cp) and tip speed ratio (TSR) of 3 model turbines calculation. The VAHT 3 blades represents conventional turbines, while VAHT-SBC 6 blades and VAHT-SBC 9 blades represent the innovative turbines proposed in this study.

The higher the Cp, the greater the power that can be extracted by a turbine. The highest Cp produced by VAHT-SBC 9 blades (Cp of 0.42 at TSR 2.19), followed by VAHT-SBC 6 blades and VAHT 3 blades. The Cp value of 0.42 has reached 93% of the maximum theoretical Cp value.

The addition of SBC causes to an increase in lift force and moment inertia which has an impact on increasing torque and Cp. VAHT 3 blades, VAHT-SBC 6 blades, and VAHT-SBC 9 blades have the same diameter and height, so the swept area of the turbines is also same. The addition of SBC can increase energy extraction without increasing turbine dimensions. It was found that Cp and torque of VAHT-SBC 9 blades and VAHT-SBC 6 blades (using SBC mechanisms) higher than VAHT 3 blades (without SBC mechanism).

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