An Experimental Investigation of Passive Variable-Pitch Vertical-Axis Ocean Current Turbine

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Abstract. Vertical-axis hydrokinetic turbines with fixed pitch blades typically suffer from poor starting torque, low efficiency and shaking due to large fluctuations in both radial and tangential force with azimuth angle. Maximizing the turbine power output can be achieved only if the mechanism of generation of the hydrodynamic force on the blades is clearly identified and tools to design high-performance rotors are developed. This paper describes an initial experimental investigation to understand more of the performance on vertical-axis turbine related to the effect of fixed-pitch and passive variable-pitch application using airfoil NACA 0018. Comparative analysis according to aspects of rotation and tip speed ratios was discussed. Information regarding the changes of foil position in passive variable-pitch during rotation at a limited range of flow velocity variations test was obtained and analyzed.

Keywords: *NACA 0018; ocean current turbine; passive variable-pitch, vertical axis.*

1 Introduction

Research and application of marine current energy conversion devices have been developed in countries such as Denmark, USA, UK, France, Norway, Italy, and several countries in Asia such as China and Japan [1]. Salter [2] performed an analysis on the changing angle of attack occurred in the blade and concluded that the vertical-axis turbine can achieve comparable performance values (following Betz's theory) with the type of horizontal-axis turbine. Darrieus turbine blades typically use aerofoil sections designed as in wind turbine. The NACA 0012, NACA 0015, and NACA 0018 profiles, and two chambered airfoils NACA 4415 and HLIFT18 were studied as blade sections [3]. The main aerodynamic models that have been used for performance and design analysis of straight-bladed Darrieus-type for VAWT briefly described by Islam [4]. Batten, et al. [5] also conduct a numerical model of a typical 3D rotor to demonstrate parametric variations of the design parameters and the use of alternative blade sections for ocean current turbine. Calcagno [6], presenting results on experimental and numerical approaches to the development of a prototype vertical-axis turbine types of ocean currents, and Kobold is an application that was first performed using 3-straight NACA 0015 series. Although studies have been conducted

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on the NACA 0018, information and performance of characteristics for vertical axis ocean current turbine for passive variable-pitch need to be more closely examined.

In this study, prototype of vertical-axis ocean current turbine test was constructed to determine the effect of a fixed-pitch and passive variable-pitch application using NACA 0018. Changes in rotation and tip speed ratio resulted at the speed variation between 0.6 - 1 m/s are presented. The dynamics of blades position on azimuth of rotation due to pitch-type application was analyzed as more in-depth information about the characteristic of turbine.

1.1 Lift and Drag of VAT

A distinction is made between vertical axis turbines that operate using the drag force of the flow on its rotor and those that employ lift forces to generate torque. Drag type devices employ a blade shape that has a higher drag coefficient with flow incident on one side than on the other. In this way the downstream drag force on the retreating blades is greater than the retarding force on the blades advancing in flow on the other side of the rotor. A net torque is thus generated. It is a limitation of drag type turbines that higher speeds and higher peak efficiencies cannot be attained due to the speed of the rotor is inherently limited because the blades on the retreating side will never travel faster than the current. In addition, relatively large amounts of material are required for a given swept area. However construction is typically simple and inexpensive compared to other types of turbine.

Lift type turbines, such as the Darrieus turbine, employ aerofoil-section blades to generate lift. Such turbines are able to convert this lift into positive torque when the blades are traveling sufficiently fast relative to the free-stream flow. Consider the two-dimensional case of a blade moving in a circular path. as shown in Figure 1. As the blade rotates, it experiences a changing relative flow, which is the vector sum of the local flow speed and the blade’s own speed. Both the angle of incidence of this relative flow and the magnitude of its velocity vary with the orbital position of the blade, called the azimuth. In general, the relative flow always comes from the upstream side of the blade: that is the outer side of the blade on the upstream pass and the inner side on the downstream pass. Thus, the angle of attack swings through positive and negative values each revolution. At small non-zero angles of attack the lift force generated by the blade has a tangential component in the direction of rotation. Provided that drag is small, the blade then contributes positive torque to the rotor on which it is mounted. This torque is used to drive a load, thus extracting energy from ocean-current. In the absence of a free stream, the angle of attack is at all times zero and no lift is produced.

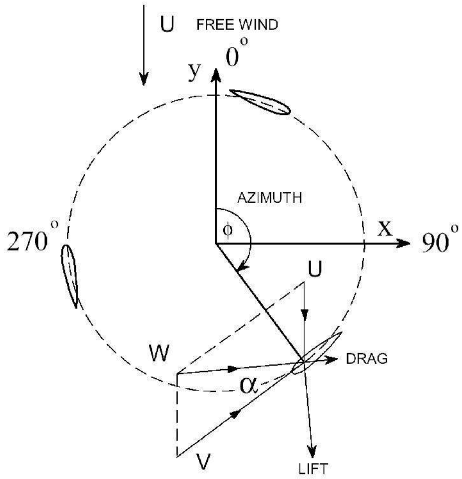


Figure 1 Illustration of Darrieus concept.

2 Experimental Model

Experiments which include the manufacturing and testing of the work piece were performed at the towing tank facility Hydrodynamics Laboratory Faculty of Marine Technology of ITS (Figure 2), with the following specifications:

- Length : 50 m
- Width : 3 m
- Depth : 2 m

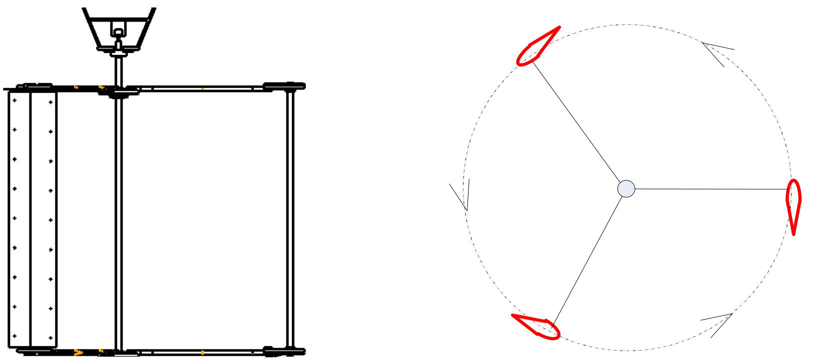
Figure 2 Towing tank facility

Model has the following geometric parameters:

- number of blades tested : 3
- blade chord : 0.1 m
- blade airfoil : NACA 0018

- blade span : 1 m
- Aspect Ratio : 10
- radius : 0.5 m (Diameter 1 m)
- number of radial arm : 6

The blade chord is set at 0.1 m, giving an aspect ratio of 10, with 0.5 m arm to the main shaft. The turbine is designed with three blades. Initial analysis of 4 symmetrical NACA 4-digit foils [7] suggested that NACA 0018 had the best characteristics for vertical axis tidal current turbine. The NACA 0018 profile was chosen as the blade section with data from Sheldahl and Klimas [8]. This foil is commonly used for Darrieus turbines because it has relatively high thickness to chord ratio hence gives it good strength in bending. The radial arms of the turbine were made from high strength aluminium. Turbine shaft uses cantilever type with one end fixed by the bearing and the other end free (overhanging) as shown in Figure 3.



(a) Slide View (b) Top view

Figure 3 Three straight blade vertical axis turbine.

2.1 Obtaining Passive Variable- Pitch

The inability to start rotating due to stalling of the blades at low and intermediate tip speed ratios occurs when the angle of attack becomes too large. If the angle of attack can be reduced properly, the flow over the blade may remain attached. This reduction in angle of attack requires that the foil orientation be changed to point closer to the apparent flow direction. Reduction of stall is the principal mechanism by which variable-pitch increases torque at intermediate TSRs, but the concept may also produce significant improvements at start up and low TSRs. Below TSR 1, it is not practical for a blade to pitch sufficiently quickly to prevent stall.

The basis for the passive variable-pitch concept is that a blade that is free to pitch along a spanwise (longitudinal) axis near leading edge will seek to point into the apparent flow. Mechanism to obtain the foil angle of freedom is based on the stall angle for NACA 0018 series [8]. Numerical validation at *Re* 80000 has been carried out [9] and provides the first stall at AoA of 10^0, and the next is at AoA of 45^0 as shown in Figure 4. At AoA higher than this the aerofoil undergoes stall: the flow separate from the upper surface of the foil causing a loss of lift and an increase in drag [10].

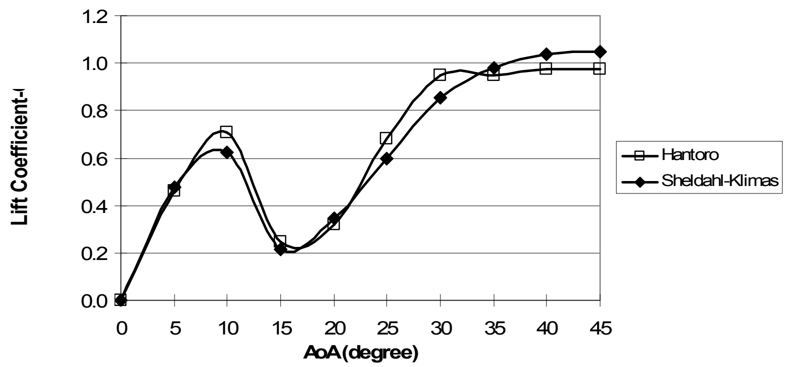


Figure 4 Numerical validation at *Re* 80000.

Kirke and Lazauskas [8] provides the shifting of AoA due to increasing of *Re* (Figure 5). The *Re* increment as a function of upstream velocity gives greater AoA to stall.

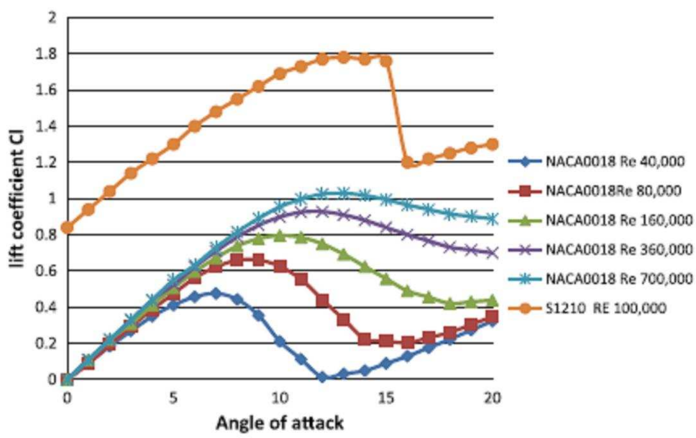


Figure 5 Shifting of AoA due to increasing of Re.

According to the first stall at AoA of 10^0 the Restrictions of pitch freedom in this experimental study was taken at 10^0 of AoA, this is due to the close AoA before the first stall occurred and facilitate in blade setting during test. The position of passive variable-pitch gives the freedom to move within the interval -10^0 to 10^0, as shown in Figure 6.

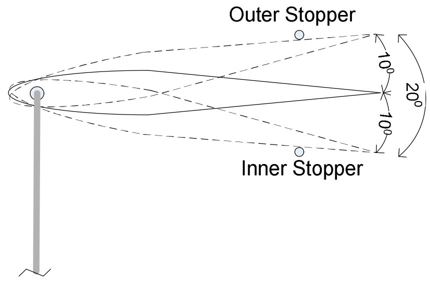


Figure 6 Fixed-pitch and passive variable-pitch position at foil.

Changes in pitch angle position with 3 (three) freedom identified conditions, namely in the middle position between the two stoppers (mid), the position of sticking/stuck stopper outside (out), and the position of sticking/stuck in the stopper (in). Identification of such position and the turbine rpm are obtained by video recording from a mounted camera and take during the testing. The rotation (rpm) is obtained from the number of rounds in a certain time interval on the camera when the carriage speed has been stabilized. Changes of an initial velocity when the carriage begin to move, achieving stable, and down again to stop recorded on a data acquisition system located in control room. The view of turbine position from the camera mounted on the train and move with the carriage is shown in Figure 7.

Figure 7 The view of turbine from camera position on the carriage.

2.2 Calibration of Speed Variation

Carriage speed operation of the system is done by tuning the voltage at the control room with range of 2-10 volts. Carriage speed and the generated voltage is measured by velocity-meter and voltmeter which mounted on wheels and motor trains. They are recorded on the existing application tool in control room as shown in Figure 8.

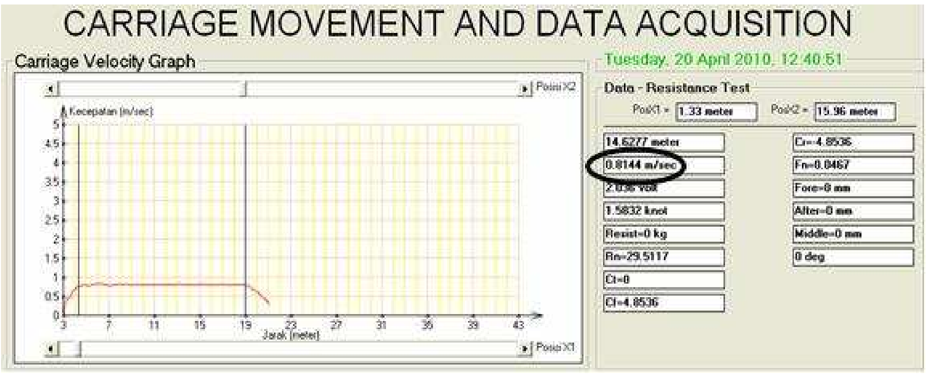
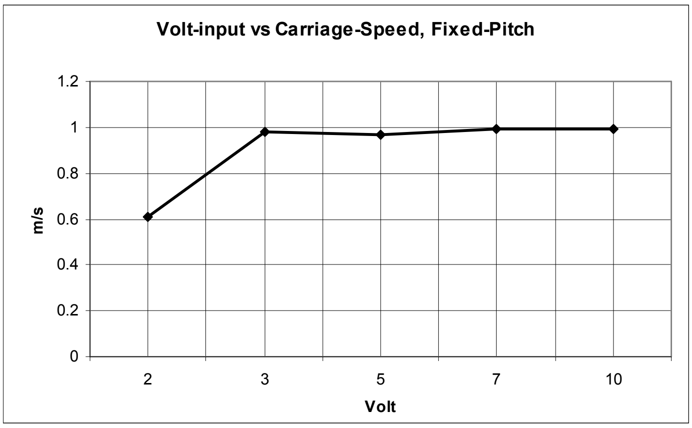


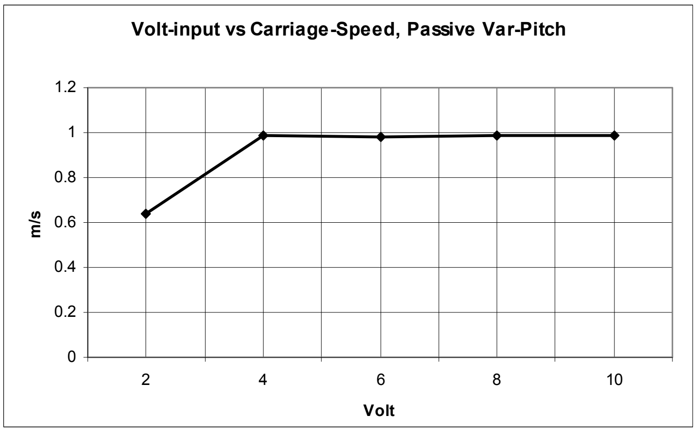
Figure 8 Example: Data Record and display of carriage speed measurement result at 2 volts voltage tuning.

From the initial data it is known that there are limitations on the speed variation of start tuning voltage input >3 volt, mainly because above this value does not give measurable changes in the value of train velocity, shown in Figure 9.



(a)

Figure 9 Volt change in input to the measured speed of the train, (a) on fixed-pitch, (b) on passive variable-pitch ***(continued)***.



(b)

Figure 9 Volt change in input to the measured speed of the train, (a) on fixed-pitch, (b) on passive variable-pitch.

3 Vertical-Axis Turbine Test

As data obtained in the previous test has limited number due to inability to pull carriage on the velocity variation, test performed by varying the speed of 0.6 – 1 m/s to obtain sufficient amount of data to identify changes of rpm. Data are obtained for speeds between 0.6 – 1 m/s shown in Table 1 and Figure 10.

Tabel 1 Rpm turbine at a speed of 0.6 m/s – 1 m/s.

		Fixed-pitch		Passive Variable-pitch	
No.	**Volt-input**	**U (m/s) measured**	**rpm**	**U (m/s) measured**	**rpm**
1	2	0.6	0	0.6	28
2	2.2	0.7	0	0.7	31
3	2.4	0.8	37	0.8	37
4	2.6	0.9	39	0.9	41
5	2.8	1	42	1	45

Start of rotating capabilities of fixed-pitch turbine occurs at speed of 0.8 m/s (Figure 10), at this speed turbine to rotate at 37 rpm. On the other hand, passive variable-pitch turbine rotates at speed of 0.6 m/s with the same rpm on a fixed-pitch, which is 37 rpm. Increased of rotation at the same flow rate using passive variable-pitch have a larger trend when compared with the fixed-pitch. This is consistent with many researchers finding that start of rotating capabilities is one disadvantages of vertical axis turbine types [2,11].

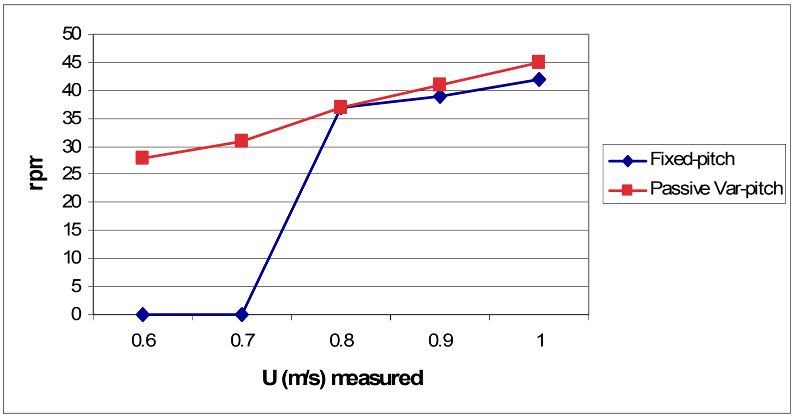


Figure 10 Turbine rotation between 0.6 - 1m/s at intervals of 0.1m/s.

Average rotation increases with respect to flow velocity of 0.1 m/s, incremental value a test of fixed-pitch is 2.5 rpm/0.1 m/s. Whereas testing of passive variable-pitch is 4.25 rpm/0.1 m/s. The trend shows a linear pattern in the interval of 0.6 m/s to 1 m/s. According to rotation produced in Table 1, TSR values is determined and shown in Table 2. With a range of value of the TSR is 0-7 [12], the working area of turbine in the study has an intermediate value of TSR between 2.2 - 2.4.

Tabel 2 Value of tip speed ratio on the test result.

u - m/s	TSR- fixed pitch	TSR- passive variable pitch
0.6	0.0	2.4
0.7	0.0	2.3
0.8	2.4	2.4
0.9	2.3	2.4
1	2.2	2.3

Tabel 3 Comparison rpm for speed variation the same for the passive variable-pitch.

Passive variable-pitch			
No.	**U-m/s measured**	**rpm**	
		Erwandi [10]	**Hantoro**
1	0.6	26	28
2	0.7	32	31
3	0.8	35	37
4	0.9	41	41
5	1	44	45

The implementation of passive variable-pitch is confirmed by other previous test. Erwandi [13] perform experiment in towing tank at hydrodynamic laboratory Indonesia (BPPT-LHI) using the same airfoil series and give a close agreement, as in Table 3 and Figure 11.

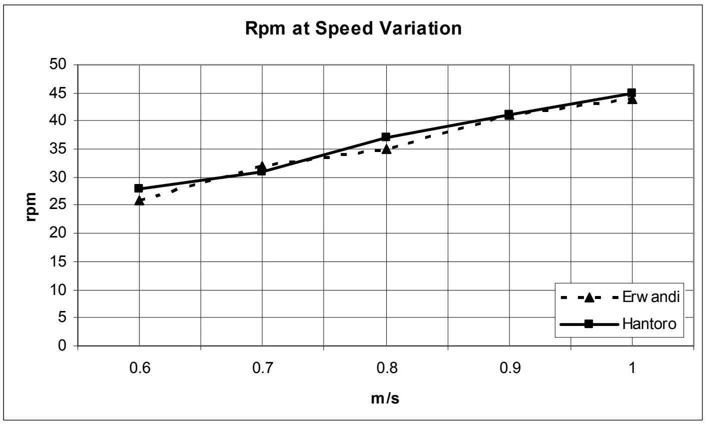


Figure 11 Comparison of rpm for the same speed variation of passive variable-pitch.

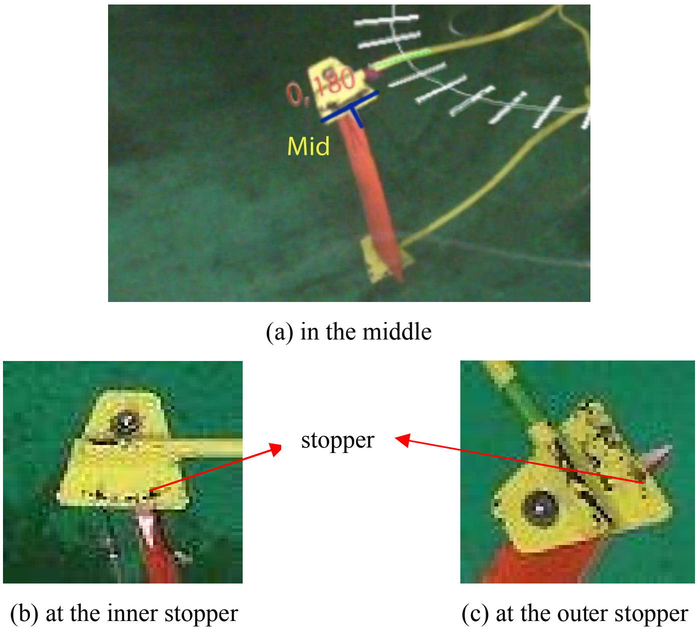
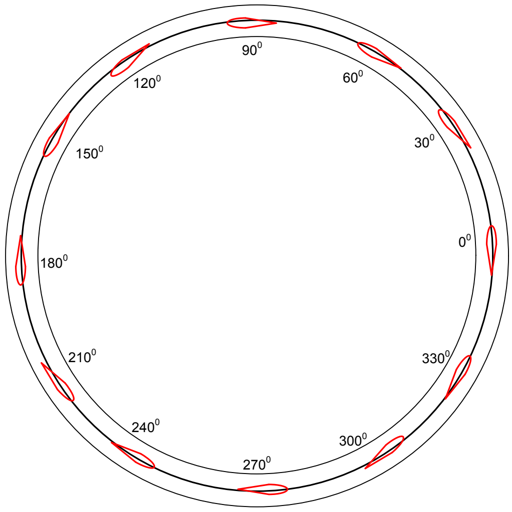
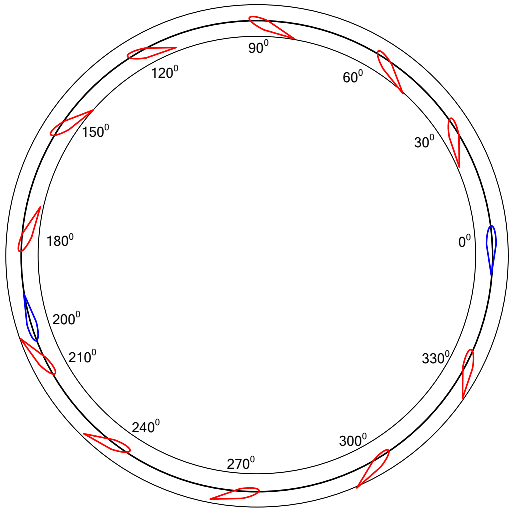


Figure 12 Identification of foil position in azimuth of rotation.



(a) fixed-pitch



(b) passive variable-pitch

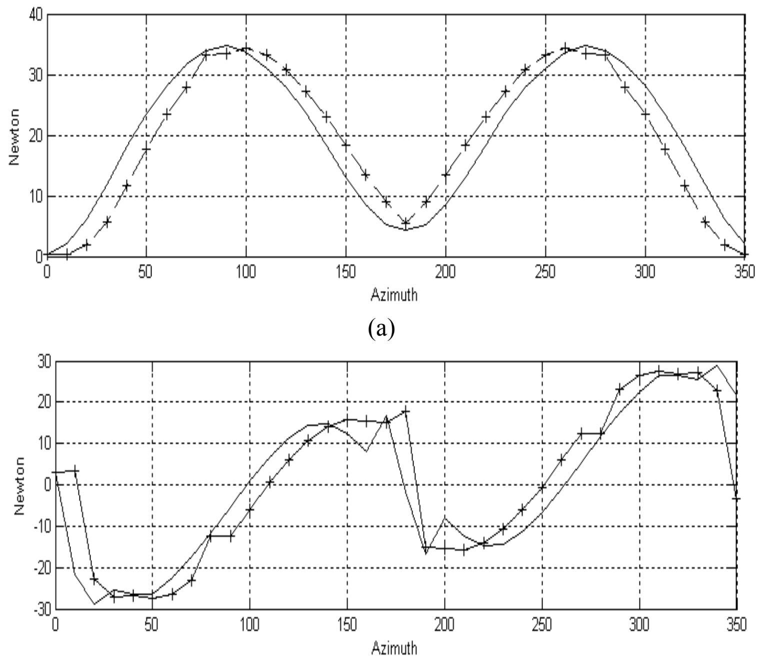
Figure 13 Changes in pitch angle of the azimuth, (a) fixed-pitch, (b) passive variable-pitch.

Camera used in the study was set to record at 60 fps (frame per second) and gives 60 frames/pictures for one second video record. The dynamics of pitch angle on fixed-pitch and passive variable-pitch is identified using video record with respect to azimuth position of a foil and time needed for a rotation. Example of video extraction to obtain a foil position is shown in Figure 12.

Differences in the changes of pitch angle on the azimuth angle of rotation using two types of pitch were shown in Figure 13. For passive variable-pitch (Figure 13.b) at the azimuth angle 0^0 and 200^0, foil are in the middle position between the two stoppers. At the azimuth angle 0^0 < azimuth <200^0 foil touches the inner stopper, while the azimuth angle 200^0 <azimuth <0^0 foil touches the outer stopper.

Foils inclined to the flow, such as those on passive variable-pitch turbines have shown improvement in self-starting behavior, because inclined foils experience smaller excursions of angle of attack and therefore are stalled over a smaller range of azimuth angles rather than similar foils oriented parallel to the axis of rotation.

Numerical prediction of the Lift and Drag force fluctuations on a blade was given by Hantoro [14]. Comparison of changes of the force fluctuations on a fixed-pitch and passive variable-pitch for stand-alone blade is given in Figure 14.



(a)

(b)

Figure 14 Force fluctuations comparison on an individual blade at U = 0.8 m / s, (a) the direction-x and (b) y-direction.

The use of a passive variable pitch provides shifting of 10^0 in phase of Drag and Lift generated with respect to azimuth. Shifting of Drag by $+10^0$ occurred at azimuth of 10^0-180^0 and decreased by -10^0 at azimuth of 190^0-350^0. Whereas the phase changes of Lift force increase by $+10^0$ at 10^0-220^0 azimuth and decreased by -10^0 at azimuth of 230^0-350^0. Implementation of passive variable pitch provides increasing of Lift at the majority of azimuth between 10^0-350^0 and to become one of the factors which contribute to the phenomenon of better self-starting.

4 Conclusions

Implementation of passive variable-pitch blade mechanisms to improve the aspect of performance of the three straight-bladed vertical axis ocean current turbines has been carried out through experiment test. Towing tank test of a prototype turbine featuring two type concepts has also been undertaken. NACA 0018 foil which is used in this research with flow velocity variations of 0.6 – 1 m/s provide data on capability of start rotating at speed 0.8 m/s for fixed-pitch condition, and at speed <0.6 m/s for passive variable-pitch which proves better ability to start rotating at intermediate TSRs of 2.3 - 2.4.

The use of passive variable pitch give the effect of phase shift of the lift and drag in accordance with the angle of freedom given (10^0), so the potency occurrence of stall on the blade angle was minimized. apart from the effects of the stall angle, the use of passive variables also provide increased of lift at the majority of position of azimuth in the rotation of turbine.

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