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Effect of Pitch Angle on the Performance of Horizontal Axis Hydrokinetic Turbine for River Application

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Kinetic energy of river current can be a promising source of consumable energy if suitable technical solution is developed. One of the most suitable ways of harnessing energy from river current is to harness it by means of a horizontal axis hydrokinetic turbine. Assessment of pitch angle is a factor of paramount importance in design of a horizontal axis turbine as it has a powerful impact on the efficiency of turbine. This research attempts to investigate the effect of pitch angle on the performance of a hydrokinetic turbine when the turbine is applied in a river. The investigation was performed through few experiments on a twin bladed horizontal axis hydrokinetic turbine changing the pitch angle of the blades. A prototype of river power system with a turbine and a dc generator was used to conduct the experiments. An elaborate analysis on the performance of the turbine at various pitch angles is presented in this paper. The results indicate that turbine with small pitch angle performs better at higher river velocity and turbine with large pitch angle performs better at lower river velocity.

Field of Research: Mechanical Engineering

1. Introduction

The global attention on renewable energy is increasing day by day due to the rising awareness about the limited resource of fossil fuel and its harmful impacts on environment. One of the largest reservoirs of renewable energy is river, which contains vast amount of energy in the form of kinetic energy. Unlike wind and solar energy this is a predictable source of renewable energy. Harnessing energy from river current using kinetic mechanism requires a hydropower system with two basic components: a hydrokinetic turbine and an electricity generator. Hydro-kinetic turbines are zero head energy conversion devices which produce mechanical energy utilizing kinetic energy of moving water. The use of kinetic mechanism makes the system less environmentally detrimental than the conventional hydro-energy system, which uses the difference between water levels. On the basis of axis of rotation hydrokinetic turbine are classified into two types: Vertical axis hydrokinetic turbine and horizontal axis hydrokinetic turbine. The horizontal axis turbine has some beneficial feature which makes it more suitable than vertical axis turbine in most applications. The most significant advantages of horizontal axis turbine are: easier self-starting, less torque fluctuation, higher efficiency and high speed operation.

Horizontal axis hydrokinetic turbine, when placed in moving water converts the kinetic energy of water into lift force, which is utilized to produce torque to drive the generator shaft. The amount of generated lift force is dependent significantly on the blade pitch angle which is the angle between the blade cord and the turbine rotation plane. As the pitch angle has a vital effect on the performance of turbine, the efficient design of horizontal axis turbine requires proper assessment of blade pitch angle.

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Many studies have been conducted on hydrokinetic turbine involving the effect of pitch angle and most of those studies are on ocean application. Effect in the river case still needs to be deeply explored, since there are some differences between the characteristics of kinetic energy of river and ocean. The ocean turbine operates at a high water velocity and experiences high flow fluctuation, while river turbine operates at a lower velocity and experiences relatively less flow fluctuation.

Due to the typical low velocity of river the kinetic mechanism of river turbine becomes less economically attractive, since the performance is the function of the cubic velocity of water. Thus to make the application of river turbine economically feasible the turbine is needed to be designed precisely, and proper assessment of pitch angle is an essential requirement for this purpose. Accommodating this requirement behavior of a horizontal axis river current turbine at various pitch angles was studied and analyzed in this research. The main objective of this research was to find out how the performance of a hydrokinetic turbine varies with the variation of blade pitch when the turbine is applied in a river. The investigation was accomplished by conducting few experiments on a prototype of hydropower system.
This paper demonstrates the whole procedures that were executed to perform the research as well as describes the background and outcomes of this research. A literature review of the technology that was dealt with is presented in Section 2. The materials that were used and the methodology that was implemented in this research are described in section 3. Section 4 deals with the outcomes and the reason behind the outcomes of this research. Section 5 concludes the topic mentioning significance and limitation of this research.

2. Literature Review

In the energy conversion mechanism of horizontal axis hydrokinetic turbine, the intercepted kinetic energy of moving water is converted into lift forces by the blades of the turbine which have cross sections of airfoil shape. The lift force produced by the blades is then utilized to generate torque for driving the generator shaft in order to produce power. The lift force is generated through the acceleration and deceleration flow at above and below of the blade section. This acceleration and deceleration flow is a result of the deflection of fluid created by the shape of the cross section and the blade pitch. These two different flow conditions create the difference in the static pressure between the regions at above and below the section to produce the lift force. Thus, for the horizontal axis turbine, there is a close relation between the pitch angle and the generated lift force.

In wind domain, there are a lot of studies available which deal with the relation between pitch angle and performance of the horizontal axis turbine. Studies of Rudion et al (2004) and Musyafa et al (2010) show that the adjustment of pitch can control the output power of the turbine in the variation of the wind speed. Study of Atmadi et al (2009) shows that very small pitch angle and very large pitch both results in poor turbine performance. A report on a field work (2007) of Seventh Generation Energy System shows that the adjustment of the angle improves the annual energy output by almost 8%. Study of Zhang et al (2008) shows that the adjustment of the pitch retains the power output when the wind speed is above the rate.
In water domain, there are also many studies relating to the effect of pitch angle on the performance of hydrokinetic turbine. Study of Batten et al (2006) on a horizontal

axis ocean turbine using a mathematical model and a cavitation tunnel shows that the low pitch angle enables turbine to gain power at a low velocity. Coiro et al (2006) investigated the effect of the pitch angle on the performance of a horizontal axis marine current turbine using the towing tank at the University of Naples Fredico II. The result indicates that at a low rotation, the turbine with higher pitch angle performs better than those with lower pitch angle. Balaka and Rachman (2012) investigated the pitch angle effect on river current turbine by a parametric study with the mathematical model of the Blade Element Momentum theory. The result of their investigation shows that efficiency of a river current turbine increases with the increase of pitch angle up to a certain level, however further increase of pitch results in low performance and reduces the rotation operation which in turn requires a high gearing ratio of the transmission system. Though a lot of researches have been conducted in wind and water domain to find out the effect of pitch angle on the turbine performance, river current turbine has been deprived of adequate attention. Therefore, more studies are needed to be conducted to investigate the effect of pitch angle on the performance of river current turbine for the purpose of efficient design and economic implementation of river power system.

3. Material and Methods

The investigation of turbine performance through practical experiments requires some essential tasks to be accomplished properly for desired outcomes. Some issues such as collection of materials, site selection, design and fabrication of turbine and experimental set-up are needed to be considered with paramount importance to acquire exact result. In this research all these essential tasks were completed by adopting a systematic approach as described below:

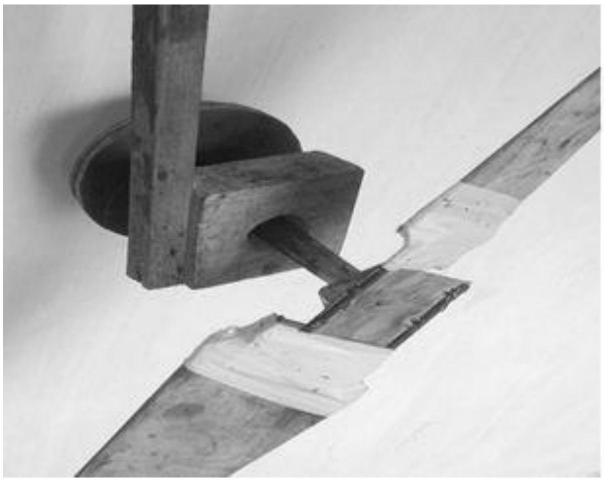
3.1 Site Selection

Experiment on a turbine practically in a site may yield some difficulties and require a lot of effort. These difficulties can be reduced by making proper selection of site. An ideal site for research may differ from a site for commercial electricity production, as the purpose of an experimental setup is to take measurements under various conditions rather than to produce electricity at a competitive price. In this research, five different sites on the river karnafuli, a renowned river of Bangladesh were chosen for experiment considering some factors such as: suitable velocity, variations in current velocity, depth and width of the waterway. Near the bank of the river the velocity of water varies with the variation of distance from the shore. To avoid this fluctuation of velocity sufficient distance was maintained from the shore.

3.2 Design and Fabrication of Turbine

Design and fabrication of a horizontal axis hydrokinetic turbine is a complex task where the engineer is faced with many design choices which will affect the turbine performance. In this research a twin bladed hydrokinetic turbine was designed and fabricated for conducting experiments. The blades of the turbine were made with pure wood and shaped as NACA 0012 airfoil. The blade length and swept area of the turbine were 0.255m and 0.23m^2 respectively. The blades were adjoined to the hub with a rectangular metal sheet which enabled the blades to undergo angular displacement when sufficient amount of force is applied. Hence it was possible to change the pitch angle of the turbine with the application of sufficient force. The thickness of blades and metal sheet were such that the turbine was capable of sustaining the thrust of river current.

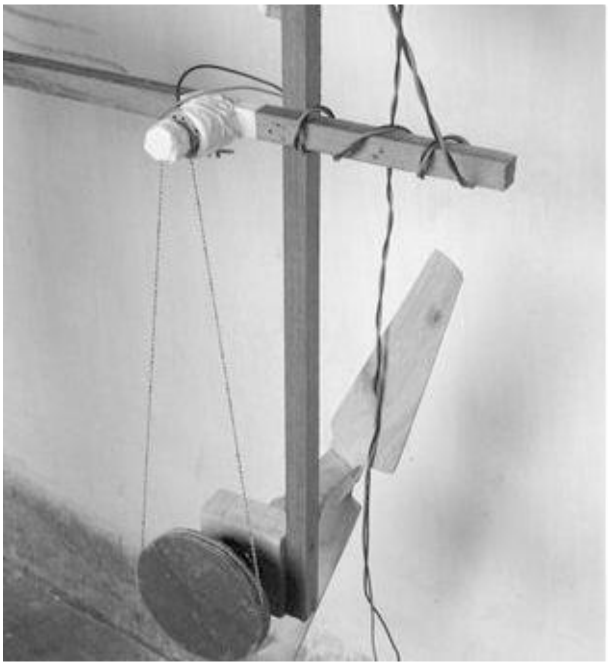
Figure 1: Fabricated Turbine



3.3 Generator Selection and Coupling with the Turbine

The turbine was coupled with a dc generator to build up a prototype of hydropower system. As the main concentration of the study was on the turbine performance, the capacity and efficiency of the generator was not considered with importance. A simple 12 volt dc motor was connected to the turbine to perform as a generator. The mechanical energy from the turbine was relayed to the generator shaft by means of belt-drive.

Figure 2: Fabricated Power System



3.4 Experimental Set-up and Data Collection

Preparation of flawless experimental set-up is an essential requirement for any experiment. During this research, before the start of every experiment turbine, generator, measuring devices and other equipment necessary for the experiment were conveyed to the site and integrated properly to prepare experimental set-up. The generator was fixed to a rigid structure and kept above the water while the turbine was placed under the water. A multimeter was connected to the output terminals of the generator by electric wire for measuring the short circuit current and open circuit voltage. A Tachometer was used to measure the rpm of the generator shaft. The rpm of the turbine shaft was calculated using rpm of the generator shaft since they were connected by belt .There were five sites having different water velocity where experiments were conducted. In every experiment turbine rpm, short circuit current and open circuit voltage for pitch angles of 5˚,15˚and 35˚ were recorded. The experimental data found from the five experiments conducted in five different sites are shown in table 1.

Table 1: Turbine Rpm, Short Circuit Current & Open Circuit Voltage at Various River Velocities for Pitch Angle of 5˚, 15˚ & 35˚

River Velocity m/s	Turbine rpm			Short circuit current Ampere			Open circuit voltage Volt		
	5˚	15˚	35˚	5˚	15˚	35˚	5˚	15˚	35˚
0.57	34	43	32	0.095	0.13	0.08	2.5	3.30	2.5
0.65	40	49	36	0.12	0.17	0.10	3.1	3.70	2.9
0.78	51	61	41	0.20	0.25	0.13	4.0	4.50	3.25
0.83	55	65	43	0.23	0.27	0.14	4.3	5.20	3.38
0.94	67	75	46	0.29	0.32	0.17	5.3	6.40	3.6

3.5 Power Coefficient and Power Output Calculation

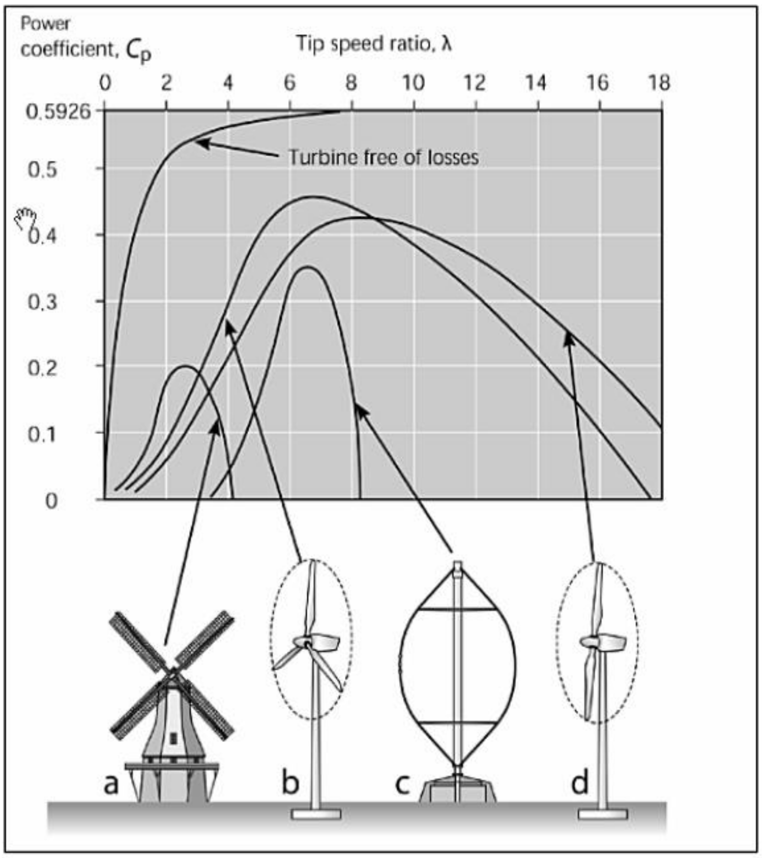
The energy extraction capability of a turbine is expressed by power coefficient which is ratio of power extracted by the turbine to the total power contained in the intercepted water. Power coefficient tells us how efficiently a turbine converts kinetic energy of water into mechanical energy. The value of power coefficient C_P is dependent on the type of turbine and the value of tip speed ratio λ, which is the ratio of linear speed of the tip of the turbine to the velocity of the water. It can be described as:

$$\lambda = \frac{\omega \times r}{v} \qquad (1)$$

Where, ω is rotational speed of the turbine [rpm]; r is the radius of the rotor [m] & v is the velocity of river [m/s];

The relation between C_P and tip speed ratio for various types of turbine is shown in figure 3.

Figure 3: C_P Curves for Different Types of Turbine (Wizelius, 2007)



As the turbine was coupled with a dc generator, the performance of the turbine was also reflected by the power output of the generator. Power output of the generator is equal to the voltage induced between the terminals multiplied by the short circuit current as described in the following equation.

$P=VI$ (2)

Where, P is power output of the generator; V is open circuit voltage &I is short circuit current.

Tip speed ratio calculated using equation (1), power coefficient found from figure 3 and power output calculated using equation (2) at various river velocities for pitch angle of 5˚, 15˚ and 35˚ are shown in table 2.

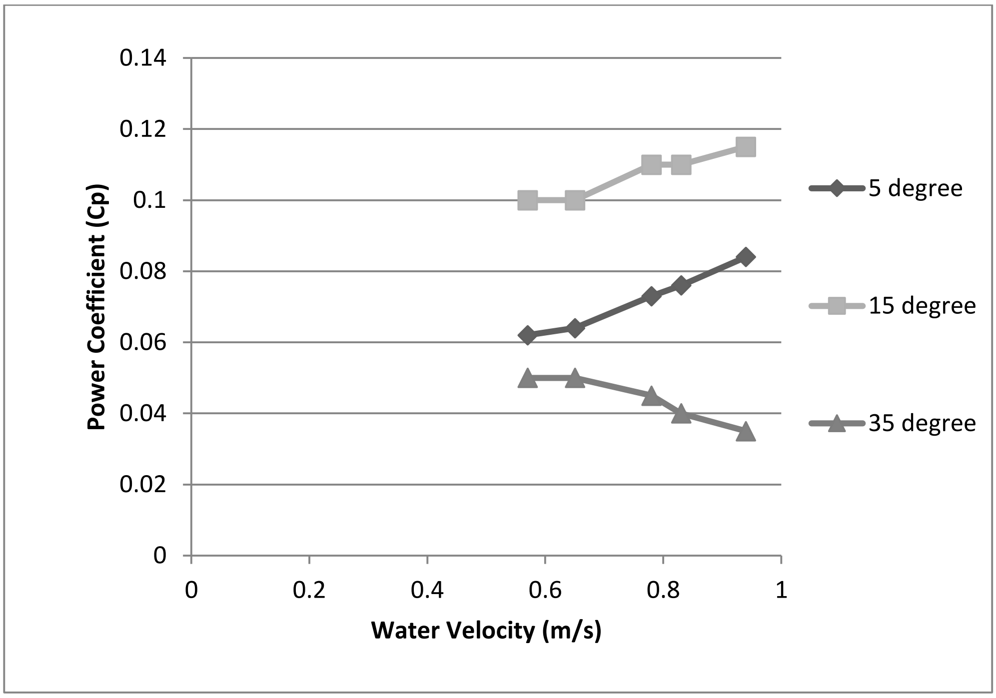
Table 2: Tip Speed Ratio, Power Coefficient and Power Output of the Generator at Various Pitch Angles.

River Velocity m/s	Tip Speed Ratio			Power Coefficient C_p			Power Output of Generator (Watt)		
	5˚	15˚	35˚	5˚	15˚	35˚	5˚	15˚	35˚
0.57	2.00	2.53	1.88	0.062	0.10	0.05	0.24	0.43	0.20
0.65	2.06	2.53	1.85	0.064	0.10	0.05	0.37	0.63	0.29
0.78	2.19	2.62	1.77	0.073	0.11	0.045	0.80	1.12	0.42
0.83	2.22	2.63	1.74	0.076	0.11	0.04	1.00	1.40	0.47
0.94	2.39	2.67	1.64	0.084	0.15	0.035	1.54	2.00	0.61

4. Results and Discussion

Analysis on the experimental data yielded from this research provides some significant information about the behavior of hydrokinetic turbine under various pitch angles. As represented in figure 4, at pitch angle of 5˚ the value of power coefficient C_P increases with the increase of water velocity. It indicates that, for 5˚ the turbine converts kinetic energy of river current into mechanical energy more efficiently at higher river velocity. In other words, at pitch angle of 5˚ the turbine yields better performance at higher river velocity. In case of 15˚ the value of C_p also increases with river velocity but this time it increases at a lower rate. On the other hand, at 35˚ the value of C_p decreases with the increase of river velocity. So at pitch angle of 35˚ the turbine performs better at lower river velocity.

Figure 4: Water Velocity vs. C_p



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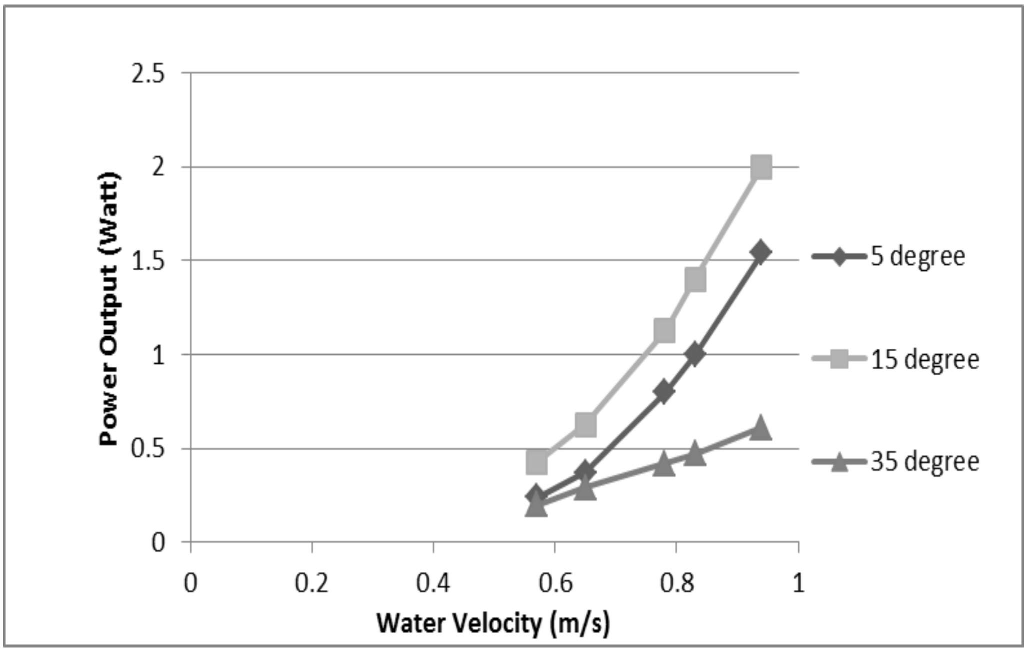
It is also evident from the figure that, at a definite water velocity the power coefficient for pitch angle of 15˚ has a greater value than that it has for 5˚ and 35˚. This indicates that the turbine extracts energy more efficiently at 15˚ than that it extracts at 5˚ or 15˚. So small pitch angle like 5˚ and large pitch angle like 35˚ both produce low power coefficient while medium pitch angle like 15˚ results high power coefficient. Thus it is better not to select a very small or very large pitch angle while designing a river current turbine if higher energy extraction efficiency is desired.

Figure 5 represents power output of the generator at various water velocities. As generator draws mechanical energy from the turbine and converts it into electrical energy at a definite efficiency, the performance of the turbine is reflected by output of the generator.

Figure 5: Water Velocity vs. Power Output



The figure clearly shows that with the increase of water velocity power output of the generator continues to increase at a steep rate for pitch of 5˚, while it increases at a much lower rate for 35˚. Power output of the generator is totally dependent on the amount of power extracted by the turbine from the river current. Therefore it can be said that, with the increase of river velocity the turbine pitched by 5˚ becomes more efficient in extracting energy from river current than the turbine pitched by 35˚. It is also very clear from figure-5 that for a definite water velocity the system produces highest amount of power at pitch angle of 15˚, while small pitch angle like 5˚ and large pitch angle like 35˚ both results in lower power output.

Thus, analysis on the basis of C_p at various river velocities and analysis on the basis of power output of the generator both indicate that turbine with small pitch angle performs better at higher river velocity and turbine with large pitch angle performs better at lower river velocity. Besides, it is also clear from above discussion that too large pitch angle and too small pitch angle both result poor turbine efficiency.

5. Conclusion

Rivers are characterized by low velocity of water which makes the application of hydrokinetic turbine less economical. At such low velocity proper selection of pitch angle turns to be a vital requirement for achieving desired efficiency. The result of this research clearly illuminates how the pitch angle affects the performance of river current turbine, and provides a guideline for selection of pitch angle. However, more research should be conducted for better understanding of the effect for wide range of water speeds and under different circumstances. While conducting this research there appeared few difficulties which shortened the scope of this research. It was a tough job to conduct experiment at river prevailing the thrust of water flow; otherwise it would be possible to collect more data during the experiments. It would have been possible to get a better idea if the performance of the turbine had been studied for few more values of pitch angle. Moreover, the outcome of this experiment would have been more precise if more data had been collected. However, this research provides some significant information which can be used for selection of pitch angle in design of river turbine. The outcome of this research suggests that assessment and change in pitch angle should be performed on the basis of river velocity for efficient implementation of river current turbine. The pitch angle of river current turbine should not be made too small or too large as that may reduce the output and efficiency of the turbine. If the velocity of the river gets higher the blades of the turbine should be set at a smaller pitch angle since turbine with small pitch performs better at high velocity. On the other hand if the velocity decreases blades should be pitched by wider angle to get better efficiency. If selection and adjustment of pitch angle is performed in this fashion the application of river power system will be more effective and economic.

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