# Hydraulic Pitch Control Technology for Tidal Current Turbine *

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## Abstract

Tidal energy is potentially a large renewable energy, which can be harnessed for electricity generation by a tidal current turbine. A pitch control mechanism is necessary for a horizontal axis tidal current turbine to work in bidirectional tidal current and keep the output power constant at above rated velocity. In this paper, a hydraulic pitch control system and the pitch actuator are designed and the performance of them are studied. The simulation results and experiment results testified that the designed hydraulic pitch control system could satisfy the requests of the tidal current turbine.

KEYWORDS: tidal current turbine, pitch actuator, power control, hydraulic driven

## 1. Introduction

The enormous demand for the energy, the exhaust fossil energy and serious environmental problems derived from the traditional fossil resources, etc. makes more and more attentions be given to the renewable energy such as wind energy, ocean energy, solar energy and so on. The ocean can accommodate huge renewable energy which are inexhaustible and free. The published documents show that the worldwide tidal energy exceeds 500 TWh/yr /1, 2/ and China owns about 50 TWh/yr tidal power capacity /3/.

Tidal current energy has some distinct advantages, such as high predictability, regularity and high power density, etc. which make the exploitation of tidal current energy more attractive. On the other hand, tidal current energy is benign to the environment. Therefore, many countries are engaged in the researches of tidal current power exploitation, including UK, Canada, Italy, Norway, China and USA, etc. and

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more and more researchers are believed to be joining the researches. Vertical axis turbine and horizontal axis turbine are the two main types of mechanism which are used to tap tidal energy, and rapid progress have be made in recent years for both of them, especially the horizontal turbines. From the earlier parachute system and "Coriolis" system (USA, 1976) to the 1.2 MW Seagen system in 2008 which is the largest ocean current power unit in the world /4/, many novel tidal current energy conversion prototypes have been tested, such as the seaflow system (300 kW, Tidal current turbine Ltd UK, 2003) /5/, the Stingray (150 kW, Yell Sound off the Shetland Islands, 2002) /6, 7/, the TidEl tidal stream generator (SMD Hydrovision, UK), DeltaStream turbine (Tidal Energy Ltd, UK), the Evopod Tidal Turbine (Ocean Flow Energy Ltd. in England), Free Flow System (35 kW, the Verdant Power Company, USA) and so on /8-10/. In addition, the Clean Current Power Systems Incorporated (Canada) /11/, the Openhydro Corporation /12/ in Ireland, the Hammerfest Strom in Norway (300 kW Tidal Stream Turbine) /13/, the Lunar Energy Ltd. based in the UK /14/, the Atlantis Resource Corporation Ltd. in Singapore and London UK (400 kW Nereus and Solon Tidal Turbines and 500 kW Solon Tidal Turbine have been tested in 2008 /15/), all carried out research works on the horizontal axis tidal current turbine (HATCT). The Wales Swansea University (in UK) has developed a direct-driven tidal current turbine /16/. The vertical axis turbines are also developed, such as Darrieus-type vertical axis turbines (Blue Energy Ltd. Canada), KOBOLD turbine (Ponte di Archimede, Italy, 2003) /17/, the Gorlov Helical Turbine (GCK Technology Inc. USA) /18/.

In China, some universities or institutions have been always engaged in the tidal current convertors. The researchers in Harbin Engineering University (HER) have been primarily focused on the vertical axis tidal turbine from 1980's. And the Ocean University of China tested its 5 kW vertical axis turbine in 2008. The researches on the horizontal axis tidal current turbine are carried on by Zhejiang University (ZJU) who tested the 30 kW turbine in 2009, and Northeast Normal University (NNU) who developed a 2 kW multiple-blade turbine running in the low speed current (lower than 1 m/s) and tested it in Dec 2005. In 2010, under the support of the Ocean Energy Special Funds, more corporations have joined the researches of tidal energy utility, such as China National Offshore Oil Corporation, China Energy Conservation and Environmental Protection Group, China Datang Corporation, Huaneng New Energy Industrial Co., Ltd. Harbin Electric Corporation, etc.

The vertical axis turbine has the advantage of without regards to the flow direction, and the disadvantages of low efficiency, unfavourable self-start characteristic, and so on. In order to improve the turbine efficiency, maximum output control mode (Nihon University in Japan) and pitch control (Reggio Calabria University in Italy and University College London in England) were investigated for the vertical axis tidal turbine (VAMCT) /19-21/. In spite of the efficiency improvement, the pitch actuation and control units of a horizontal axis turbine are used for the dual-direction tidal current flow and power stability control. This paper will present a hydraulic pitch actuator of a horizontal axis tidal current turbine. A pitch system of a 20 kW prototype was designed and manufactured, and its performance tests was carried out in the workshop.

## 2. Pitch actuator design of a tidal current turbine

The gravitational pull of the moon causes water to flow in from the ocean on the flood tides, and outward during ebb tides, so in most places the flow is dual-directional and its velocity changes in the form of sinusoid. In order to work in this periodical current for the horizontal tidal current turbine, a pitch control system is necessary, whose roles can be summarized as follows. Firstly the pitch mechanism helps the blades rotate by 180 degree (**figure 1**). Secondly, the turbine torque can be adjusted by changing the pitch angle to help the turbine rotate in low velocity. At last, the power output can be kept constant through the pitch control when the velocity is above rated.

In fact, the pitch control systems was initially studied in the wind turbine, and the purpose was to limit the turbine rotational speed and electrical output within the rated ones. Besides, the pitch system can be used to the load control, which was also studied in large turbines. The principle of the pitch control of the tidal current turbine was like that of the wind turbine by and large.

### 2.1. Pitch control theory

In order to operate in bidirectional flow, a tidal current turbine needs a pitch control mechanism or yaw system to ensure the pressure surface of a blade airfoil facing the coming water, and so when the current direction altered, the blades or the hub needed to be rotated by 180 degree. Here the pitch system was favored for its less inertia moment rather than the yaw system. When the pitch actuator was used to substitute for the yaw system, it is a position-controlled system and has two demanded values. So here it don’t need fast response but precise position tracking.

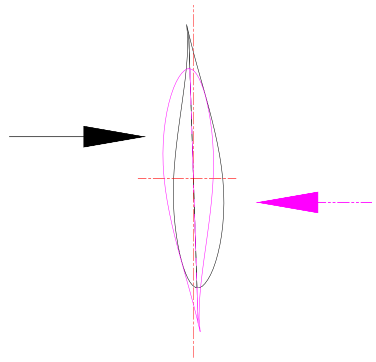

**Figure 1:** Impression of 180° pitch rotation

Another important application of the pitch control is for power regulation. As was dissertated in many documents, the power extracted from the tidal current by tidal turbine could be presented $P = \rho S v^3 C_p/2$, where $\rho$ is the water density, $S$ is the swept area of the turbine, $v$ is the velocity of flow, and $C_p$ is the power coefficient of the turbine /22/. As can be shown from this formula that when $v$ exceeds the rated, $P$ can be kept constant if the $C_p$ is controlled according to $C_p \propto 1/v^3$. **Figure 2** gives the curves of $C_p$ - $\beta$ - $\lambda$ and Cp can be controlled by changing the pitch angle $\beta$.

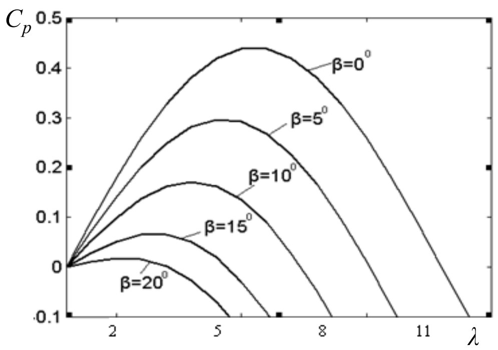


**Figure 2:** Relation curve between $C_P$ - $\beta$ - $\lambda$

When the pitch control is used to regulate the power, the pitch change system has to act rapidly, in order to limit power excursions due to short-term riptide to an acceptable value. In the practical design, the rated power was usually set as the demand value, see **figure 3**.

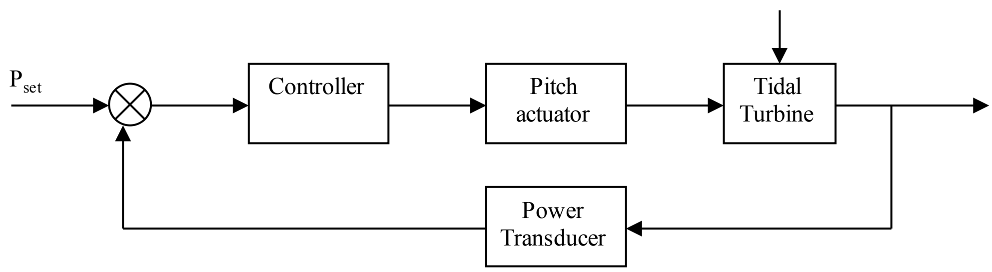


**Figure 3:** Pitch control for power stability

## 2.2. Pitch actuator

An important part of the pitch-controlled turbine is the pitch actuation system. In the research of the horizontal axis tidal current turbine reported all over the world, some pitch control technologies was used, such as the 300 kW Seaflow in UK and strom unit in Norway /23, 24/. At the early stage of pitch regulation, researches of the pitch actuator can refer to that of the wind turbine and ship's propellers or hydro turbines /25, 26/. But different from the equipments above mentioned, the blade pitch angle of the tidal current turbine needs to be controlled in the range of 180 degree or more.

Nowadays a variety of pitch actuation systems could be adopted. The blades could be pitched collectively or individually. The collective pitch system commonly consists of push-rod, which was driven by a hydraulic cylinder or ball-screw and ball-nut (driven by a servomotor) arrangement. The advantages of collective pitch control was that the pitch actuators could be located outside the hub, producing fore-aft motion of the push-rod which changed the pitch angle through a rack-pinion or other mechanical linkages. Compared with the collective pitch control, the individual pitch control system required separate actuators in the hub for each blade and so bigger space in order to fix the individual pitch actuators.

In this chapter, the pitch actuator adopted in 20 kW tidal current turbine will be researched. Considering the features of small space in the hub and the demand of 180° blade rotation, the collective pitch actuation system was adopted, and a rack and pinion gearing was used. The rack was driven by hydraulic cylinder and engaged with the gear which was coupled with the blades by bolts. **Figure 4** shows the structure of pitch actuation system.

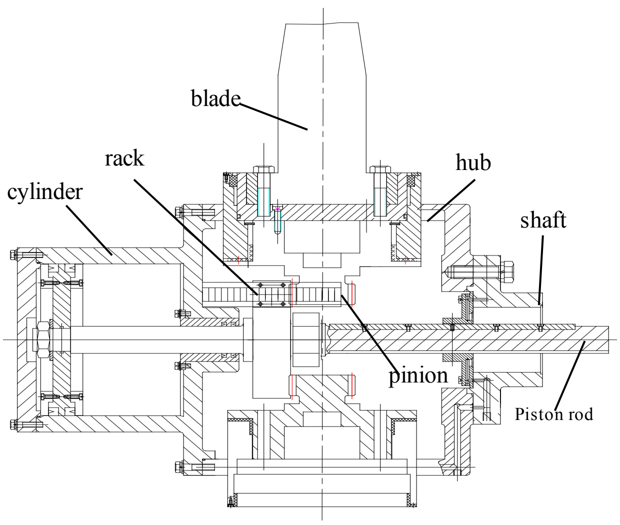


**Figure 4:** Pitch actuation system

The apparatus has following advantage. (1) During the operation of tidal turbine, the blades were endured large pitching moments, and the sliding bearings are used in order to increase the rotation damp of the blades, and at the same time the pitching moments are resisted mainly by the piston rod driven by the hydraulic system. (2) The cylinder is placed before the hub to simplify the gearbox structure, and the oil is transmitted through the hole in the wall and two holes in the main shaft. **Figure 5a** is a rotary hydraulic joint used for hydraulic actuators, and when the blades are wanted to be feathered, the oil goes from the inlet to outlet, and conversely for the backpaddling. (3) Angle measure is necessary for the pitch regulation, and the measured angle needs to be compared to the pitch angel demand so that the error control signal can be generated. Here considering the small space in hub and the inconvenience of the slip rings, the measure of pitch angle *β* is converted to the measure of the piston rod displacement *y*. The contactless magnetostrictive displacement is used, thus the slip rings can be dispensed with. Then the *β* is given by the following formula:

$$\beta = \beta_0 + \frac{2\pi}{L} y$$

Where $\beta_0$ is initial angle of the pitch, *L* is the engagement length of the rack, equal to the circumference of the pinion.

Another key problem is the seal system, and two measures were adopted. Firstly some o-ring seals were used, which can be suitable for low velocity conditions, secondly, the structure was designed like a labyrinth seal whose gaps between the rotating parts could be adjusted by the joint bolts. **Figure 5b** is the pitch actuation of 20 kW full-scaled unit.

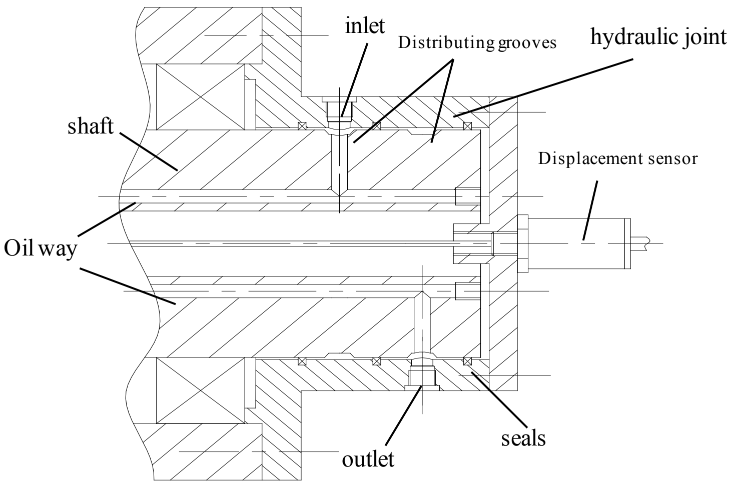


**Figure 5:** (a) Rotary hydraulic joint, (b) Test of the pitch system

## 3. Hydraulic driven system of the pitch control

As was mentioned above, hydraulic and electric actuators are the two methods to be commonly used for the pitch control, each of which has its own particular advantages and disadvantages. For the hydraulic system actuator, its most components could be placed above the water surface and don't need large space in the hub, at the same time it can afford large force for the pitch actuation. Compared with the hydraulic actuators, the electric actuators need the gearbox to elevate the pitch driven torque and lower the blade pitch speed, so the large space in the hub is needed and appropriate slip rings are also required.

Before the design of the actuation system, load analysis is necessary. The friction in the pitch bearing is often a significant factor in the design of the pitch actuator. The bearing friction depends on the loads applied to the bearing, and the large overturning moment acting on the bearing can lead to very high levels of friction. Besides, these following forces also need to be considered such as the pitching moment of the blade attributed to the coincidence between the equivalent hydraulic fore acted on the blade and the blade rotating axis, inertial moments induced by the centrifugal force of the blade, inertial moments of the blades, etc. Normally in the small scaled turbine, the later forces are neglected for its less quantity mass of the blades.

**Figure 6** gives the principle of the hydraulic system designed for the pitch actuator of tidal current turbine. The hydraulic actuator was controlled by means of a electro-hydraulic proportional direction valve controlling the flow of oil to the actuator cylinder. The valve opening would be set in proportion to the pitch demand. The pitch position demand comes from the turbine controller and is compared to the measured pitch position, and the pitch-position error is turned into a pitch-rate demand through a PID control loop. An accumulator was used to afford hydraulic pressure temporally even if the motor was shut off. Besides, a throttle valve was used to change the blade pitch speed.

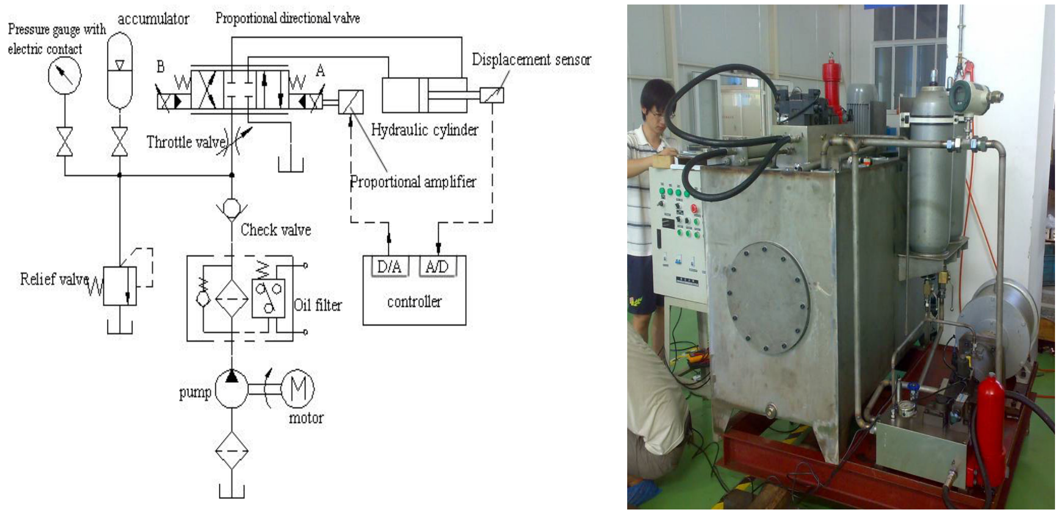


**Figure 6:** Principle and photo of the hydraulic pitch system

## 4. Simulation and experiments of the hydraulic pitch system

### 4.1. Modeling of the hydraulic system

The mathematical model of pitch control system can be constructed and simulated in Matlab/Simulink code in order to research the characteristic of the pitch system. The pitch control system was a position-controlled system and made of a valve controlled asymmetric cylinder, the rack and pinion gearing system.

Through the flow equation of the sliding valve showed in formula (1), and the hydraulic cylinder flow equation showed in formula (2), the function among $x_v$, $x_p$ and $p_L$ can be obtained. Here suppose the chamber without cylinder rod is high pressure chamber and the other is oil-return chamber.

$$q_L = K_q \cdot x_v - K_c \cdot p_L \tag{1}$$

Where, $q_L$ is the flow of the valve, $K_q$ is the flow gain, $x_v$ is the spool displacement, $K_c$ is the pressure flow coefficient of the valve, $p_L$ is the system pressure.

$$q_L = A_1 \dot{x}_p + (V_0 + A_1 x_p)\dot{p}_L / \beta_e + C_{tp} p_L \tag{2}$$

Where, $A_1$, $V_0$ are the effective area and initial volume of the chamber without cylinder rod, $x_p$ is the piston displacement of the cylinder, $\beta_e$ is the oil effective bulk modulus of elasticity, $C_{tp}$ is leakage coefficient of hydraulic cylinder.

Formula (3) gives the dynamic equation of the hydraulic cylinder according to the Newton's second law, and here the elastic load and friction were neglected.

$$A_1 p_L - A_2 p_2 = m_t \ddot{x}_p + B_p \dot{x}_p + F_L \tag{3}$$

Where $p_2$ is the pressure of the chamber with cylinder rod, $m_t$ is sum of the piston mass and equivalent mass of other components, $B_p$ is the viscosity damp coefficient, $F_L$ is the external loads.

The electromagnetic proportional valve can be considered a second-order oscillating element, and its transfer function is like formula (4).

$$G_{BL}(s)=\frac{X_V}{\Delta I}=\frac{K_{XV}}{\frac{s^2}{\omega^2{}_{BL}}+\frac{2\xi_{BL}}{\omega_{BL}}s+1} \quad (4)$$

Where $K_{XV}$ is gain of the proportional valve which is equal to the ratio of maximum spool displacement and the rated control current, $\omega_{BL}$ is natural frequency of the proportional valve, $\zeta_{BL}$ is damp ratio of the proportional valve.

The rack and pinion gearing, amplifiers were all thought to be proportional components and represented by $K$ and $K_a$ respectively. From the above analysis, the following simulation frame of the pitch system was obtained.

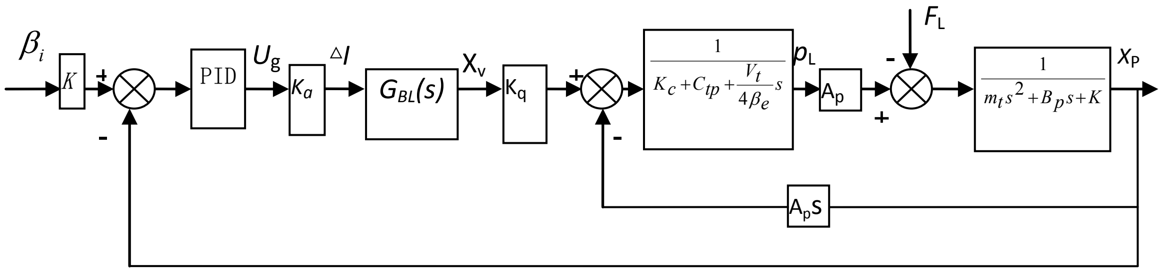


**Figure 7:** Framework of the pitch control system

## 4.2. Simulation and experiments

The performance of the hydraulic driven pitch control system was simulated in Matlab/Simulink. **Figure 7** is the simulation framework of the pitch control system. The controller adopted PID, which was testified to be applicable from the results of simulation and workshop tests. **Figure 8** gives the simulation and experiment results. In the tests, several step-inputs was used to excite the system. The overshot in the simulation result (red line) could be attributed to the neglecting of some damping, frictions, and leakages, etc. From the experiment results, the governing time of the system is about 1 s and the overshoot is zero. The pressure of the hydraulic pitch system is about 3.75 MPa.

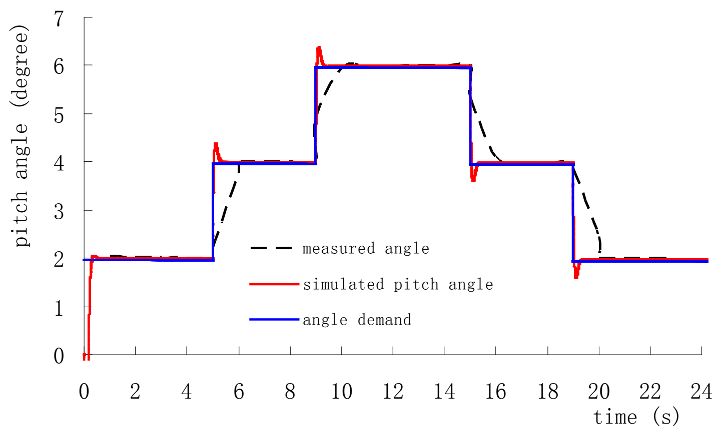


**Figure 8:** Simulation and test results of the pitch system

## 5. Conclusion

This hydraulic pitch control system in a 20 kW horizontal axis tidal turbine was researched in this paper. Through the design and tests of the equipment, some conclusions could be drawn.

Considering the characteristics of the small scaled tidal current turbine, a hydraulic pitch system was designed and testified. The simulation and experiment tests verified its feasibility.

Besides, the pitch system could be used to control the power output. When the flow velocity exceeds the rated one, pitch can be feathered to reduce the power capture. When the velocity is below rated, the blades are fixed at the optimal pitch angle.

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