PRELIMINARY INVESTIGATION OF A FLAPPING VERTICAL AXIS WIND TURBINE

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Vertical axis wind turbine (VAWT) is one of the promising wind energy conversion systems and many ideas are proposed to improve this performance. In this paper, newly designed Flapping VAWT (FVAWT) system performance is discussed. We will discuss the efficiency of this system using with a simple two dimensional hydrofoil theory and compare the performance of fixed type VAWT and FVAWT. Numerical calculation shows the FVAWT is 15% higher performance compared with the fixed type VAWT system without any external energy supply.

Keyword: Flapping Foil, Vertical Axis Wind Turbine, Hydrofoil Motion Foil Control

1. INTRODUCTION

Fixed type VAWT such as H type or Darius type wind turbine are simple but rather poor performance is reported compared to the cycloidal one. In the foil azimuth angle is near zero degree, which zone is the maximum relative velocity acting on the foil, both VAWT foil system can't generate trust or foil rotating torque but only generate the drag force or negative turbine driving torque. It is well known that the flow energy is proportional to the cubic of the flow speeds; therefore if we introduce some mechanisms to generate the foil thrust or driving torque with small mechanical loss, this may increase these VAWT performances. In this system, it will distribute the absorbed energy in one foil circular motion to the energy of the foil heaving damping works and acting as the optimization of the total energy gain.

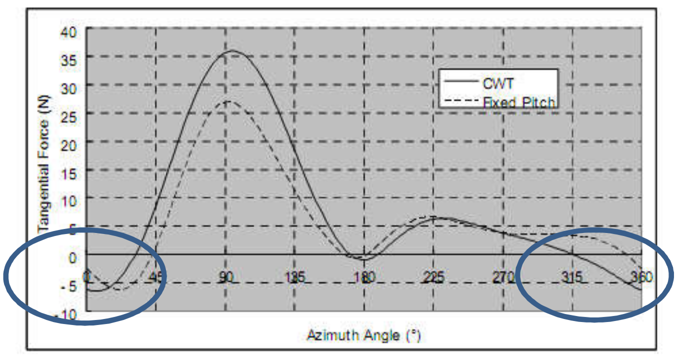

Figure 1. VAWT hydrofoil thrust (tangential) force.
In the azimuth angle 0 and 180 deg., negative thrust force zone appeared.

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In a system with a vertical-axis hydrofoil, even a pitch-controlled system that theoretically should be able to achieve optimum efficiency, no torque is produced when the relative flow rate is a maximum. When such a turbine is rotating, right at the point when the wind becomes a head wind, the hydrofoil is simply subject to resistance, so naturally no torque is generated that would cause the hydrofoil to rotate.

However, because the wind flow speed rate relative to the hydrofoil surface at this point is a maximum, if it was possible to have the air strike the hydrofoil at a certain angle, thrust and torque could be generated. A search of the literature for information relating to this idea turned up no results.

Having come this far, the next step was to consider a hydrofoil drive mechanism designed for this purpose. With that in mind, I devised a number of feasible methods and mechanisms. The following describes one of these approaches.

2. FLAPPING VERTIVAL AXIS WIND TURBINE MECHANISM

Regardless of what method is used, it should be possible to configure a system to control the heaving motion of the rotor hydrofoil. However, the system can only be put into practical use if it is as straightforward as possible, and is highly robust. I came up with a number of mechanisms that would satisfy these requirements, and here I will describe one that is highly promising in terms of practical use.

Let us consider the performance of a VAWT that rotates while generating a heaving motion in the hydrofoil. One way of controlling the hydrofoil motion would be to have an arm with joints, which would fold to control the heaving motion of the hydrofoil. Hereafter, we will call this the flapping vertical-axis wind turbine (FVAWT). Figure 2 shows a schematic view of the FVAWT with simple link system. Photograph 1 and 2 show functional model of FVAWT, with spur gear and link system, made of ABS materials with 3-D printer. The hydrofoil is set holding and open condition with link system.

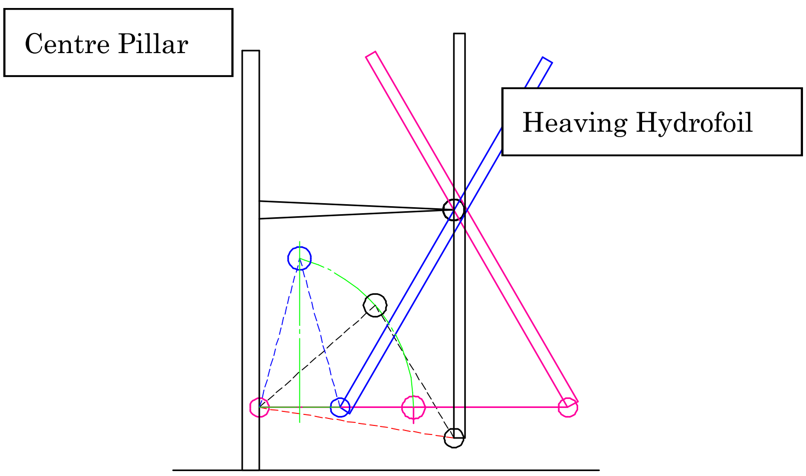

Figure 2. A concept of the foil heave motion controlled VAWT

Schematic view shows the foil's heave motion is controlled by the arms with 3 joints.

Photograph 1. Foil Closed FVAWT with spur gear.

Photograph 2. Foil Opened FVAWT with spur gear.

This method involves a new principle of hydrofoil motion. Even if the hydrofoil is a rotor hydrofoil, it can normally be controlled using two control parameters that increase the hydrofoil performance. One of these is the pitch angle of the hydrofoil, and a method using efficient hydrofoil angle control for VAWTs based on the azimuth angle and relative flow speed is already in practical use. The Voith Schneider propeller uses this method.

In this section, I evaluate the performance of a VAWT, based on the idea of controlling the heaving motion of the rotary hydrofoil and improving the energy absorption efficiency. The reason that I have not previously come across an idea such as this may be because of the centrifugal force generated by the rotor hydrofoil.

However, devices have already been researched and developed in which a hydrofoil is positioned to act in the same way as the tail fin of a fish in a uniform flow such as an ocean or tidal current, causing the hydrofoil to vibrate and absorb the energy of the flow.

3. ENERGY BALANCE

In order to control the heaving motion of a rotating hydrofoil, let us look at the energy balance required. To make the hydrofoil undergo heaving motion, we need to identify where the energy comes from to provide that motion. That is, obtaining this energy from a part of the hydrofoil positive trust azimuth angle zone, and redistributing this kinetic energy to the negative trust azimuth angle zone. Main object is looking for a point at which the rotational energy balance becomes positive during a single rotation of the hydrofoil motion, compared to normal VAWTs as shown in Fig.3. It might be possible to implement a control principle based on this, but the hydrofoil turning trajectory would not be a perfect circle as shown in Fig.4.

Energy flow will be shown as Fig.5, and if the flapping hydrofoil absorbed energy exceed the work done by the hydrofoil, this idea and foil control system will be success.

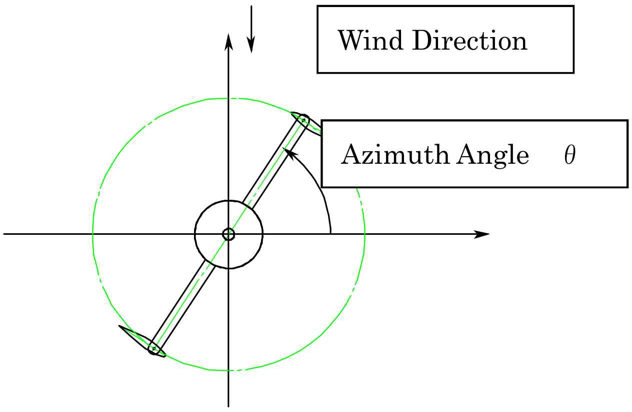

Figure 3. Normal VAWT at operation.

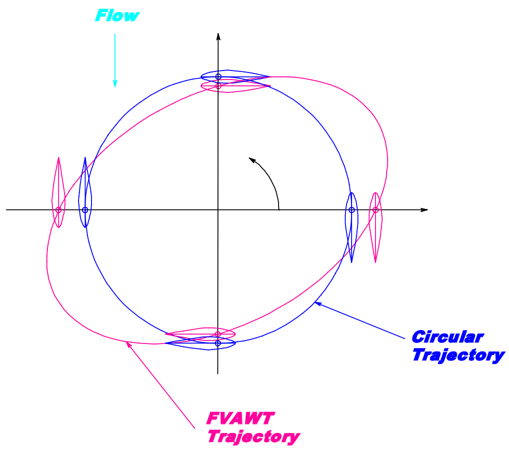

Figure 4. FVAWT foil trajectory.

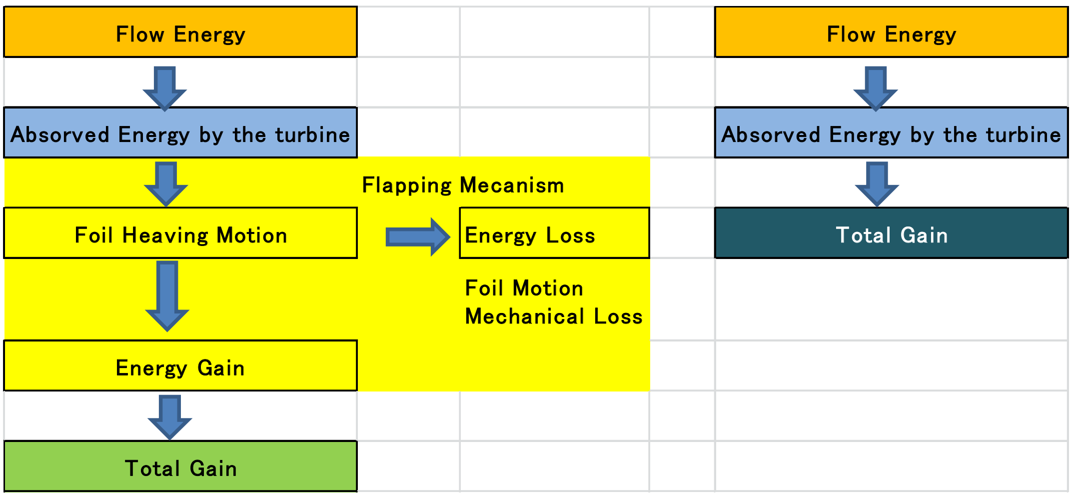

Figure 5. Energy flow diagram (left is FVAWT and right is fixed pitch normal VAWT)
Yellow zone is newly added function of FVAWT.

We will consider the energy gain about a normal VAWT hydrofoil, which undergoes simple circular motion, and an FVAWT hydrofoil, in which the trajectory changes and no more circler motion. We will carry out some numerical calculations to explore the energy balance for these hydrofoil systems.

Here, denoting the angle for which the hydrofoil is turning at the maximum relative velocity as θ=0.
The inflow rate is:

$$u = (U + r\theta) \tag{1}$$

The velocity of the hydrofoil in the vertical direction was set to be lower than this velocity. U is flow speed, r is rotating arm length and θ is rotating angle.

$$v = \dot{r} \tag{2}$$

The inflow angle is approximated as: $\alpha = \frac{v}{u}$.
Here,

$$u^2 = (U + r\theta)^2 + v^2 \tag{3}$$

$$\cong (U + r\theta)^2 \tag{4}$$

and the lift force generated by the hydrofoil is:

$$\mathrm{L} = \frac{1}{2}\rho S u^2 C_L(\alpha) \tag{5}$$

$$\mathrm{T} = \mathrm{L}\sin\alpha \tag{6}$$

$$\cong \mathrm{L}\alpha \tag{7}$$

$$= \frac{1}{2}\rho S u^2 k \alpha^2 \tag{8}$$

S is foil area, ρ is fluid density. And considering the three-dimensional lift force correction parameter k,

$$\mathrm{k} = \frac{2\pi\Lambda}{2+\Lambda} \tag{9}$$

Λ:foil aspect ratio

The thrust is given by:

$$\mathrm{T} = \frac{1}{2}\rho \mathrm{S}(\dot{r})^2 k \tag{10}$$

However, this can be evaluated as increasing the thrust,

$$\varepsilon = 1 + \{\frac{v}{(U+r\theta)}\}^2 \tag{11}$$

causing it to double. Here, for purposes of simplification, (10) is used for evaluation.

Also, at the position of the minimum relative flow rate,

$$\mathrm{u}^- = (\mathrm{U} - \mathrm{r}\theta) \tag{12}$$

Carrying out a similar approximation, then

$$\mathrm{T}^- = \frac{1}{2}\rho \mathrm{S}(\dot{r})^2 k \tag{13}$$

In this case, however, the result will contain a larger error than with the (10) approximation.

Because this thrust will always be positive, it might be possible to overcome a disadvantage of the normal VAWT, which is that the thrust of the VAWT goes from zero to a negative value.

4. NUMERICAL ANALYSIS

An even number of hydrofoils is better in terms of keeping the configuration simple, so here I used two hydrofoils. However, I calculated the hydrodynamic force acting on only one hydrofoil, and did not take hydrofoil interference into consideration. Also, I created the simplest possible hydrofoil analysis model, not taking fluid hysteresis into consideration. The reason for this is that the focal point of interest in this experiment is how the energy balance changes in response to the heaving motion of the hydrofoil.

The parameters necessary for the calculation are the hydrofoil amplitude, frequency and phase. The heaving amplitude *r* for the FVAWT is added to the rotation radius *R* for a normal VAWT. The parameter evaluated in the analysis is *r*/*R*. The rotating speed of the normal VAWT is *ω*, and that of the FVAWT is *nω*, where n is set at first as an integer value. The FVAWT system, to decide the hydrofoil heaving motion, motion phase angle must be introduced. After these parameters, the heaving motion of the FVAWT hydrofoil trajectory to be described.

Parametric survey of the dependence of the energy acquisition rate on r/R is examined under the given phase conditions for which the acquired energy is largest.

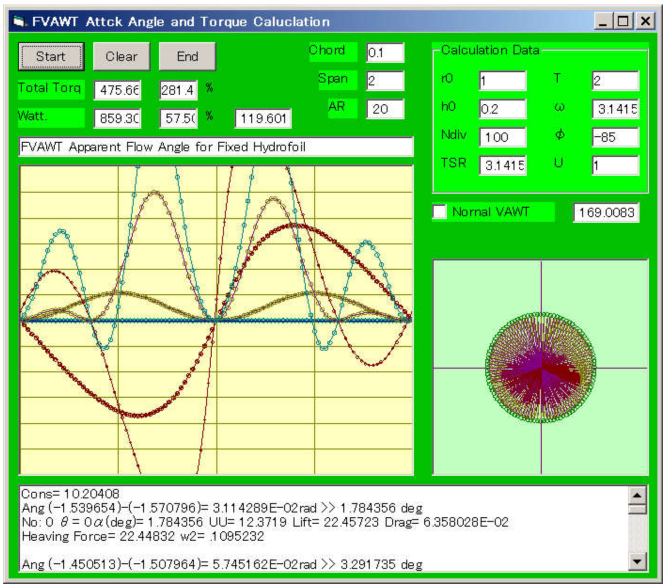

Figure 6. A sample of the FVAWT calculation.

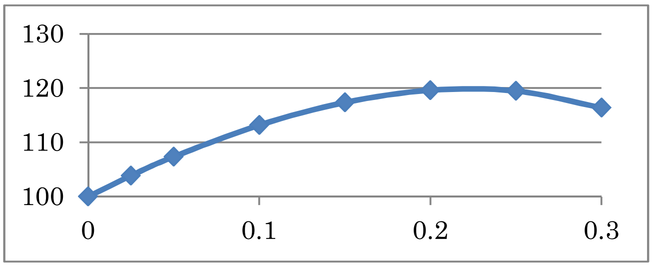

Figure 7. Energy gain (%) vs. heave amplitude/radius.

Fig.6 shows an example when the heaving period is set to twice the rotation period of the hydrofoil, and Fig.7 shows the corresponding gain. From Fig.7, it can be seen that when the heaving amplitude is around 20% of the rotation radius, the maximum energy is obtained. It is also clear, however, taking stalling of the hydrofoil into consideration, that it will not be possible to achieve performance at this level.

The heaving motion at this time is determined as shown below. We call n ω as the mode is n. Here, the mode is set to 2.

$$\mathrm{h(t)} = \sum_{i=1}^{n} h_i \sin(2i\omega t + \varphi_i) \tag{14}$$

If asymmetrical movement is allowed, then

$$\mathrm{h(t)} = \sum_{j=1}^{n} h_j \sin\{(2j-1)\omega t + \varphi_j\} \tag{15}$$

φ_j is j-th phase angle. In this case, the centrifugal force due to the rotation of the hydrofoil cannot be canceled, and this causes vibration. If this vibration is not considered a problem, the energy absorption can be calculated.

Let us calculate this using j=1, with mode 1. Fig.8 and Fig.9 shows calculated results. The gain changes significantly as a result of the rotational motion of the hydrofoil and the phase of the hydrofoil heaving motion. Naturally, the point of maximum efficiency is at a phase angle of 90° as shown in Fig.10.

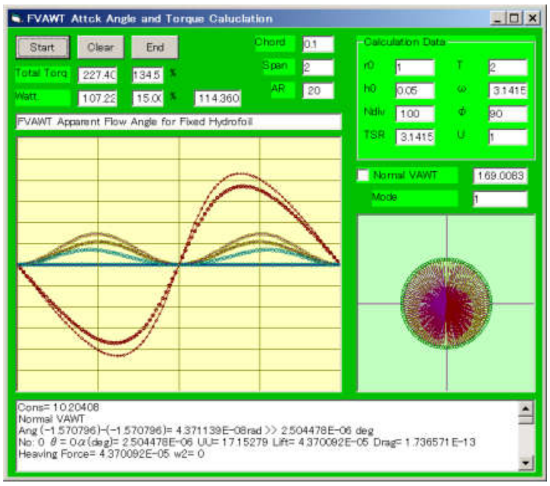

Figure 8. Efficiency of the VAWT and FVAWT at mode=1.

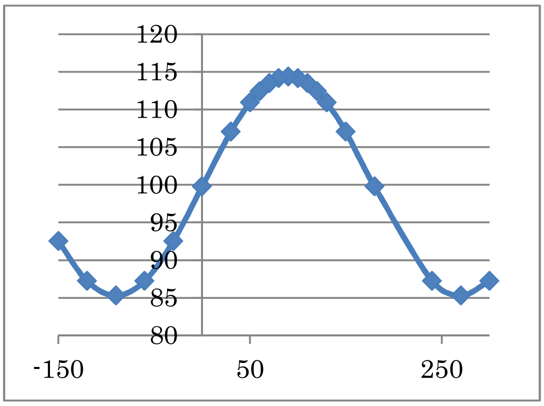

Figure 9. Gain with Mode=1, case with asymmetric heaving motion.
Heave amplitude / turning radius=0.05.

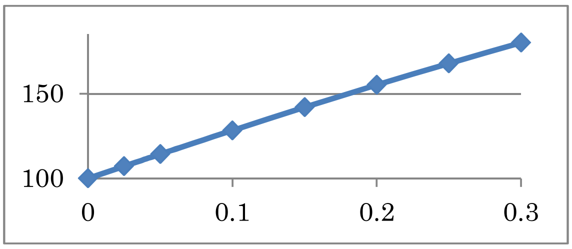

Figure 10. Energy gain(%) vs. heave amplitude/radius asymmetric motion.
Mode=1,ϕ = 90deg. I must expect the foil stall phenomena in this case.

Following intuition, the performance is calculated for different modes. The phase of the heaving motion must be correct in relation to the current flow in order to produce sufficient power. If we calculate another mode, Mode=1.5, this means three foil flapping motions is conducted while two circulating motion. As sown in Fig.11 and Fig.12, zero phase angle is optimum.

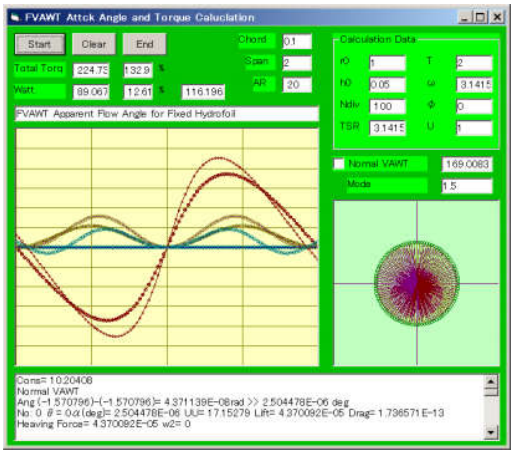

Figure 11. Calculated FVAWT performance at mode=1.5.

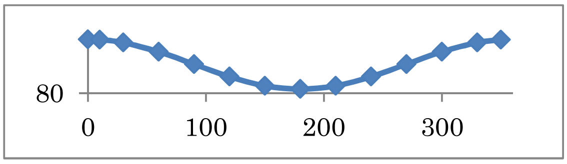

Figure 12. Phase and efficiency of FVAWT at mode=1.5.

5. CONCLUSION

In order to improve the efficiency of the VAWT based on the numeric calculation, the following guidelines were obtained for the FVAWT system.

a) The energy absorption efficiency is strongly dependent on the flapping frequency, and should be up to three times as high of main rotating frequency.

b) The amplitude ratio should be 0.2 or less.

c) In the control scheme, it is necessary to consider the phase difference with respect to the current flow.

d) For the amplitude characteristics, it is sensitive for stalling performance, has to be taken into consideration.

The calculation described here is an example of FVAWT performance evaluation using the simplest possible model. As a result, this paper describes just one aspect of performance improvement with adding the pure flapping motion of the hydrofoil.

In the future, I plan to perform higher-precision calculations using a hydrodynamic model, and to conduct experiments in a water tank in order to verify the improvement in performance of the VAWT using the new mechanism.

REFERENCE

1) Hwang. I.S, etc. 2005; Efficiency improvement of a new vertical axis wind turbine by individual active control of blade motion. http://cyclocopter.snu.ac.kr/paper/SPIE2006.pdf