Power Coefficient Estimation of Floating Axis Wind Turbine by Lifting Line Theory

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Abstract. In the development of the offshore wind turbine, the horizontal axis wind turbine (HAWT) with fixed foundation is the mainstream in the world. However, the floating type wind turbine is advantageous for Japan because the seas near Japan are deep. It is difficult for the vertical axis wind turbine (VAWT) to utilize its advantages on land. Meanwhile, VAWT is suitable for the floating type wind turbine because its gravity center is low. Besides, the performance of VAWT is hard to decrease if the rotor inclines. Among the VAWTs, the target of this research is the floating axis wind turbine (FAWT) which is expected to further reduction of the electricity cost. In this research, the performance of FAWT is estimated by QBlade which is based on the lifting line theory. The estimated power coefficient (Cp) of the 5MW FAWT is 0.49 and it is comparable with that of HAWT.

1. Introduction

In recent years, the clean, safe and sustainable energies are desired because of the global warming. Many researches on the renewable energies, such as solar, wind and tidal current power, are carrying out. Among them, offshore wind power has attracted particular attention. The mainstream of the offshore fixed wind turbine is the horizontal axis wind turbine (HAWT) with its success on land. However, since the seas near Japan are deep, the development of the floating type wind turbine is necessary.

Concerning the floating type wind turbine, one of the factors that increases the electricity cost is the construction cost of the floating body. Even though the HAWTs are widely used for the floating type wind turbine too, their structural features might be the demerit of using on the floating body. Firstly, the gravity center of HAWT is high because the power generation equipment is placed near the top of the tower. Besides, the tilt of the tower decreases the rotor performance. Thus, the floating body for HAWT should become large in order to support the large tower and avoid the tilt of the tower. Meanwhile, the low gravity center can be achieved for VAWT because the power generation equipment can be placed near the sea surface. The performance of VAWT is hard to decrease if the rotor inclines [1]. Therefore, the smaller floating body is acceptable to VAWT and the cost reduction are expected.

Among the VAWTs, the target of this research is the floating axis wind turbine (FAWT) which is expected to further reduction of the electricity cost [2]. In this research, the performance of FAWT is estimated by QBlade which is based on the lifting line theory. The estimated power coefficient (Cp) of the 5MW FAWT is 0.49 and it is comparable with that of HAWT.
2. Floating axis wind turbine

One of the problems to construct a large VAWT is the development of a large bearing which can support the heavy weight of a large rotor. MW class VAWT needs the bearing with 7 m diameter or longer. The demand for such a huge bearing is almost nothing. FAWT, which is a kind of VAWTs, does not require such a huge bearing.

In FAWT, the rotor is separated from the floating body, and placed on the spar float (Figure 1). The rotor and the spar float rotate as one by the wind like a fishing bobber. The tilt of rotor is permitted to some extent, and so the size of the spar float does not so large. The construction cost of the spar is lower than that of the commonly used floating body. The power generation equipment is placed on the other mooring floating body. The mooring floating body keeps the position of the spar with rotor and absorbs the reaction torque resulting from the power generation. The mooring floating body has no need to support the weight of the FAWT rotor and its construction cost also becomes low. Thus, the further reduction of the electricity cost is expected.

![Figure 1. Conceptual figure of a floating axis wind turbine.](image)

3. Lifting line free vortex wake simulation (QBlade)

In this research, QBlade, an open source wind turbine calculation software, is used to estimate the performance of FAWT. It consists two functions, XFOIL and LLFVW [3]. The former is used to estimate the blade performance, and the latter is flow simulation with Lifting Line Theory.

QBlade is mainly developed for analyzing the performance of HAWTs, and so there are few examples to apply it for VAWTs. Therefore, several simulation parameters need to be turned in order to estimate the performance of VAWTs with QBlade.

4. Simulation parameter turning

The 1-blade VAWT model [4] is used for the tuning of the simulation parameters. Table 1 shows the principle particulars of the model. In the referred paper [3], the QBlade developers compared the power coefficient $C_p$ estimated by using QBlade with that estimated by using 2D URANS. Here, $C_p$ of the wind turbine is defined as Eq. (1).

$$C_p = \frac{P}{\frac{1}{2} \rho AV^3}$$  \hspace{1cm} (1)

where, $P$ [W] is the actual electric power produced by the wind turbine, $\rho$ [kg/m$^3$] is the air density, $A$ [m$^2$] is swept area and $V$ [m/s] is the wind velocity.
**Table 1.** Principle particulars of the 1-blade VAWT model.

| Parameter                  | Value |
|----------------------------|-------|
| Radius of rotor [m]       | 0.85  |
| Height of rotor [m]       | 2     |
| Blade section             | NACA0018 |
| Chord of blade [m]        | 0.246 |
| Solidity                  | 0.144 |

Figure 2 shows the comparisons of the estimated $C_p$. In this figure, the label of horizontal axis “Tip Speed Ratio (TSR)” is the ratio of blade rotating velocity and wind velocity and expressed in the following equation.

$$ TSR = \frac{\omega R}{V} = \frac{2\pi Rn}{V} $$  \hspace{1cm} (2)

where, $\omega$ [s$^{-1}$] is the angular velocity of the rotor, $R$ [m] is the rotor diameter, $n$ [rps] is the number of rotor rotations.

![Graph showing comparisons of Cp for 1-blade model.](image)

**Figure 2.** Comparisons of Cp for 1-blade model.

Even though there is a difference between URANS result and those of QBlade in the low TSR region, the results of $C_p$ estimated by using QBlade show similar trend.

5. **Verification of the simulation parameter tuning**

Before estimating the performance of FAWT, $C_p$ for different two VAWTs are estimated based on the simulation parameter tuning used for the 1-blade turbine and compared with the experimental results in order to verify our parameter tuning method. One of the key parameters is the viscous vortex core size. In QBlade, the viscosity of fluid is represented by the vorticities. The velocity induced by a vortex is expressed by the Biot-Savart equation. The equation has a singularity at the center of the vortex. Therefore, a model for a viscous vortex core is used in QBlade to remove the singularity point and model the viscous core of the bound and free vortices accurately. The radius of a viscous vortex core is defined as a function of two key parameters, the time offset parameter $S_c$ and the turbulent viscosity $\delta_v$. A rough indication for $\delta_v$ was reported by Sant [5]. Concerning $S_c$, there does not exist such indication, and it is needed to prevent the vortices from having a zero core radius when being released from the trailing edge [2]. In this research, the initial core radius $r_s$ was assumed to be proportional to the blade chord length and square root of Reynolds number. Based on the simulation parameters for the 1-blade turbine, $r_s$ for the other VAWTs were calculated by the following equation.
\[ r_s = r_0 \frac{C_s}{C_0} \sqrt{\frac{Re_s}{Re_0}} \]  

where, the subscript \( s \) and \( 0 \) represent the target turbine and 1-blade turbine respectively, \( r \) [m] is initial core radius, \( C \) [m] is the blade chord length, and \( Re \) is Reynolds number. Two key parameters \( S_c \) and \( \delta_v \) were determined so that \( r_s \) satisfied above equation.

5.1. SANDIA 34-m test bed turbine

The Sandia 34-m test bed turbine (Fig. 3) was a full-Darrieus VAWT built by Sandia National Laboratories to obtain several useful data [6]. It was designed that the electrical power was 500 kW under the 12.5 \([\text{m/s}]\) wind velocity with rotating velocity 37.5 \([\text{rpm}]\). The curved blade was constructed by the different two symmetrical blade sections, NACA0021 and SAND0018/50. The former was used near the top and bottom of the blade, and the latter was used for the other part. The chords of the blade were also different at the part of a blade. This turbine was fixed to the ground and did not tilt like a wind turbine placed on the floating structure. Table 2 shows its principle particulars.

![Figure 3. The Sandia test bed VAWT [6].](image)

| Table 2. Principle particulars of the Sandia 34-m test bed VAWT. |
|---------------------------------------------------------------|
| Radius of rotor [m] | 17 |
| Height of rotor [m] | 42.5 |
| Number of blade | 2 |
| Blade section | NACA0018, SAND0018/50 |
| Chord of blade [m] | 0.971, 1.07, 1.22 |
| Solidity | 0.13 |

Above Sandia 34-m test bed VAWT model was created in QBlade, and its \( C_p \) was estimated. Figure 4 shows the comparison of the simulated results with the experimental results obtained from the Sandia report. The rotating velocity was 28 \([\text{rpm}]\) in this case. Compared with the experimental result, even though the simulated one shows the similar tendency with the experimental, the maximum value of \( C_p \) was underestimated. This was because that the blade performance of SAND0018/50 estimated by XFOIL was not appropriate.
5.2. DeepWind turbine test model

The concept of the DeepWind turbine consist of the following 4 parts, 1) a long vertical tube that rotates in the water, 2) a VAWT is placed on the tube, 3) the power generation equipment is located at the bottom side of the tube, and 4) a mooring system at the bottom of the tube [7]. In the DeepWind project, a 1 kW DeepWind turbine model was manufactured and its performance was analyzed through a wind tunnel test [8]. The DeepWind is the offshore wind turbine, and so it is important to know the performance of the turbine under the tilted condition. In their wind test, not only the upright but also the tilted turbine conditions were examined. The tilt angle was 15 [deg]. Figures 5 show the conceptual figure of a DeepWind turbine and the snapshots of the turbine condition at the wind test. Table 3 shows the principle particulars of this test model. Asymmetrical blade section DU-06-W200 was used for the curved blade.

![Figure 4. Comparison of $C_p$ for the Sandia test bed VAWT.](image)

| Radius of rotor [m] | 1.014 |
|---------------------|-------|
| Height of rotor [m] | 1.902 |
| Number of blade     | 3     |
| Blade section       | DU-06-W200 |
| Solidity            | 0.310 |

Table 3. Principle particulars of the 1 kW DeepWind turbine test model.
Figures 6 show the comparison of the simulated and experimental results under the upright and tilted turbine conditions. The rotating velocity was 200 [rpm] in this case. Compared with the experimental result, the simulation slightly overestimated the maximum values of $C_p$. However, the simulated $C_p$ curves captured the tendency of the experimental ones for both turbine conditions.

Figure 7 shows the ratio of maximum $C_p$ under the tilted condition ($C_{pt}$) to that under the upright condition ($C_{p0}$). Experimental results show that the effect of the turbine tilt become large with increase of TSR, and same tendency can be seen in the simulation result.

![Graph showing the comparison of $C_p$ under upright and tilted conditions.](image-url)

**Figure 6.** Comparison of $C_p$ for the 1 kW DeepWind turbine test model under the upright (left) and tilted (right) condition.
6. Estimation of $C_p$ for 5MW FAWT

In this research, a 5 MW FAWT was the target for its performance estimation. The rate wind velocity is 12 [m/s]. The VAWTs analyzed in the last section adapt the curved blade. Meanwhile, the straight blade is used for FAWT. The blade section is NACA0018, and it is symmetrical blade. Figure 8 shows the rotor of 5MW FAWT and table 4 shows the principle particulars of the 5 MW FAWT.

![Rotor of 5 MW FAWT](image)

**Figure 8.** Rotor of 5 MW FAWT.

| Table 4. Principle particulars of the 5 MW FAWT. |
|-------------------------------------------------|
| Radius of rotor [m]                              | 53.625 |
| Height of rotor [m]                              | 107.25 |
| Number of blade                                  | 3      |
| Blade section                                    | NACA0018 |
| Chord of blade [m]                               | 3.9    |
| Solidity                                         | 0.11   |

Figure 9 shows the estimated $C_p$ curves under the upright, 15 [deg] and 20 [deg] tilted turbine conditions. In case of the upright condition, maximum $C_p$ is 0.49 at TSR = 3.5. In the simulation, the support arms between the blade and the center shaft (see Fig. 8) were not considered, and so $C_p$ might be slightly overestimated, but the $C_p = 0.49$ is comparable with that of HAWT. Concerning the effect of turbine tilt, the maximum $C_p$ of FAWT decreased under 20 [deg] tilted condition but increased under 15 [deg] tilted condition. This can be explained the increase of the swept area. Figure 10 shows the ratio of swept area under the tilted condition ($S_{tilt}$) to that under the upright condition ($S_0$). The
ratio of swept area gradually increases with the increase of the tilt angle, and becomes its maximum around 15 [deg] tilted condition as show in Fig. 10. In case of 20 [deg] tilted, the ratio of swept area is still over 1.0. However, the effect of the blade performance degradation caused by the turbine tilt might be larger than that of the swept area increase, and the maximum $C_p$ of FAWT decreased.

7. Conclusions

In this research, in order to estimate the power coefficient of FAWT using QBlade, the simulation parameter identification of QBlade was firstly performed. Based on the simulation for 1-blade VAWT model, the method to determine the simulation parameters was derived. The initial core radius was assumed to be proportional to the blade chord length and square root of Reynolds number. The availability of the method was validated by comparing $C_p$ for other two VAWTs.

It is generally recognized that maximum $C_p$ of VAWT is lower than that of HAWT. However, simulated results show that maximum $C_p$ was 0.49 at TSR = 3.5 for a 5 MW FAWT. This value is comparable with that of HAWT. Besides, the maximum $C_p$ of the FAWT increased around 15 [deg] tilted condition because of the swept area increase. Thus, FAWT has the ability to compete against the floating type HAWT.

**Figure 9.** $C_p$ for 5 MW FAWT under the different tilt conditions.

**Figure 10.** The ratio of swept area under the tilted condition to that under the upright condition.
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