OPTIMIZATION OF COUNTER ROTAITNG WIND TURBINE USING BLADE ELEMENT & MOMENTUM THEORY

Byeong Ho HWANG[1]*, Seung Min LEE[2], and Soo Gab LEE[3]

[1]*Department of Mechanical and Aerospace Engineering, Seoul National University, Seoul, Korea*
[2]*Department of Mechanical and Aerospace Engineering, Seoul National University, Seoul, Korea*
[3]*Department of Mechanical and Aerospace Engineering, Seoul National University, Seoul, Korea*

* Corresponding author: isdn2@snu.ac.kr

In terms of the increasing efficiency of wind turbine, the maximum efficiency of counter rotating wind turbine is theoretically 64% and it is higher than 59%-maximum-efficiency[1]. A Counter rotating wind turbine has a front rotor and a rear rotor which rotate in opposite direction at the same axis. Compared to the single rotor, the flow field of counter rotating wind turbine is complicated due to interactions between the front rotor and the rear rotor. The wake induced by a front rotor is working on inflow of rear rotor and is essentially unsteady flow state. In order to estimate performance of counter rotating wind turbine, it is required to consider more variable than the case of single rotor wind turbine and to prepare the estimation system which is able to perform the delicate prediction. For optimization of counter rotating wind turbine, pitch angles, distance, radius ratio and rotation speed of two rotors are chosen for design values and variations of power coefficients and thrust coefficients are observed on this study. For reasonable comparison, the solidity is fixed. The torque of two rotors is balanced due to assuring maintenance efficiency and stability of the wind turbine systems. For analysis of whole performance of counter rotating systems, Blade Element & Momentum Theory modeling for the counter rotating wind turbine is developed to predict front rotor flow analysis and the wake flow generated by front rotor. After that the wake flow is applied for inflow of rear rotor. The vehicle test is carried out to validate prediction. According to variation of each design values, the distribution of performances and maximum point is obtained. Because of decrease of the front rotor effecting on the rear rotor, specially, whole performances are increasing when the rear rotor is longer than the front rotor at the specific ratio.

Figure 1. Operating test of the counter rotating wind turbine using vehicle

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TITLE :

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First Author(Corresponding Author) : Byeong Ho HWANG

Affiliation: Ph.D. Candidate, Department of Mechanical and Aerospace Engineering,

Seoul National University.

Address: Rm. 218, Bldg. 35, Seoul National University, Seoul, 151-744, South Korea.

Tel: 82-2-880-7299

Second Author : Seung Min LEE

Affiliation: Ph.D. Candidate, Department of Mechanical and Aerospace Engineering,

Seoul National University.

Address: Rm. 218, Bldg. 35, Seoul National University, Seoul, 151-744, South Korea.

Tel: 82-2-880-7299

Third Author : Soogab LEE

Affiliation: Professor, Department of Mechanical and Aerospace Engineering and

Institute of Advanced Aerospace Technology, Seoul National University

Address: Rm. 105, Bldg. 311, Seoul National University, Seoul, 151-744, South Korea.

E-mail: solee@snu.ac.kr

Tel: 82-2-880-7384

Fax: 82-2-875-4360

ABSTRACT

A Counter rotating wind turbine has a front rotor and a rear rotor which rotate in opposite direction at the same axis. Compared to a single rotor, the flow field of the counter rotating wind turbine is complicated due to interactions between the front rotor and the rear rotor. The wake induced by a front rotor is working on inflow of rear rotor and is essentially unsteady flow state. In order to estimate performance of counter rotating wind turbine, it is required to consider more variables than the case of single rotor wind turbine and to prepare the estimation system which is able to perform the delicate prediction. For optimization of the counter rotating wind turbine, pitch angles, a radius ratio and a rotation speed of two rotors are chosen for design values and variations of power coefficients and thrust coefficients are observed on this study. The torque balance of two rotors is considered due to kinematic coupling of generator. Blade Element & Momentum Theory modeling for optimization of the counter rotating wind turbine is developed to predict the front rotor flow analysis and the wake flow generated by the front rotor. After that the wake flow is applied for the inflow of the rear rotor. The vehicle test is carried out to validate prediction. The optimized solution is found using a multi-island genetic algorithm.

KEYWORDS

Counter-Rotating Wind Turbine, Velocity Interference, Induction Factor, Power Coefficient, Thrust Coefficient, Optimization, Vehicle Test

NOMENCLATURE

a : Axial induction factor
BEMT : Blade element momentum theory
VLM : Vortex lattice method
C_p : Power coefficient
C_T : Axial force coefficient
R : Rotor radius
r : radial distance
U_∞ : Wind velocity
ρ : Air density

1. INTRODUCTION

The wind turbine industry becomes hot-issue because renewable energies are under the spotlight around the globe. Also researches about advanced technologies of the wind turbine have been doing actively since commercial value of wind turbine is gradually rising.

A Counter rotating wind turbine has a front rotor and a rear rotor which rotate in opposite direction at the same axis. It has been proposed as a new model for advancing power efficiency. According to momentum theory by Newman[3], the maximum efficiency of a counter rotating wind turbine is theoretically 64% and it is higher than 59%-maximum-efficiency of single rotor. In order to certificate this theory, some experimental studies about the counter rotating wind turbine have been carried out.

The counter rotating wind turbine is classified as various types according to radius ratio between front and rear rotors, location between nacelle and rotors and kinds of generator. In this study, the target of the research is a small counter rotating wind turbine whose the front rotor is upwind and the rear rotor is downwind with the rear rotor is longer than the front rotor. This wind turbine has properties of the downwind rotor which is able to be a free yawing because the radius of the rear rotor is longer. So it is suitable for a small wind turbine which is difficult to equip the yawing system.

There are three types of the generator which can use in the counter rotating wind turbines[10].

A. Two independent generators, one for each rotor
B. A differential planetary gearing coupling both rotors to a single generator
C. One generator with kinematic coupling of both rotors

When generator B and C are used, the generator systems can be simplified because there is no need for second generator. So the cost of wind turbine is reduced. In case of B, high generator efficiency can be obtained since there are additional degrees of freedom. However, it is possible a maintenance cost is increasing because of a gear worn. Whereas C is no need for the gear, so the system is more simplified than B. It leads to reducing a cost of wind turbine systems. Also, because the relative velocity is used when the front rotor rotates the stator and the rear rotor rotates the armature in the opposite direction, the each rotor divides a rotational speed of the generator. It leads to decrease of the noise level which is major issue of the small wind turbine since the aerodynamic noise property of the wind turbine is proportional fifth order of the tip Mach number.

However, the front and rear rotors always rotate same shaft torque due to a kinematic coupling between the stator and the armature, so the torque balance must be considered during the design process. Each rotor rotates a different rotational speed from a design point at the operation. If torque balance is not enough to be considered, it is possible at least one rotor cannot rotate well. [6] On the other hand, it is possible that the low efficiency design is derived when only the torque balance is focused on the design process.

In this study, the optimization design for obtaining the maximum power of the counter rotating wind turbine is carried out with considering the torque balance. The prediction method for optimization is a Blade Element & Momentum Theory(BEMT) with applying a wake modeling. The validation is carried out using a vehicle test.

2. METHODOLOGY

2.1. Numerical method

BEMT is a hybrid method which combines the momentum theory and the blade element theory for an analysis of each sectional aerodynamic performance. The momentum theory is the control volume theory applying Plandtl's tip-loss function and the blade element theory is summation of the sectional thrust and torque calculated by sectional lift and drag coefficient of the airfoils. The BEMT is reliable because it is based on solid physical principles. Furthermore, the computing cost of BEMT is remarkably low, so it is suitable for the optimization process which needs a number of calculations.

The thrust and the torque by the momentum theory are

$$\mathrm{d}T_f = 4F\rho U_\infty^2 a_f\left(1 - a_f\right)\pi r dr \quad (1)$$

$$\mathrm{d}Q_f = 4F\rho U_\infty a_f'\left(1 - a_f\right)\pi r^3 \Omega_f dr \quad (2)$$

The thrust and the torque by the blade element theory are

$$\mathrm{d}T_f = N_b \rho U_{rel}^2 (c_l \cos\phi + c_d \sin\phi) r dr/2 \quad (3)$$

$$\mathrm{d}Q_f = N_b \rho U_{rel}^2 (c_l \sin\phi - c_d \cos\phi) r dr/2 \quad (4)$$

Above functions are used for determining aerodynamic performance of the front rotor.

First, the axial induction factor a_f and angular induction factor a_f' are determined using the equals of the each thrust and torque function. Second, Sectional the thrust and the torque are determined by substituting a_f and a_f' again. And finally, in order to advance an accuracy of this method, the stall delay model and Glauert's empirical function are added.

The aerodynamic performance of the rear rotor is also predicted by using BEMT method. For analyzing the inflow condition of the rear rotor, the assumption that the rear rotor in the fully developed stream tube of the front rotor is used[8].

$$U_{\infty,r} = U_{\infty}(1 - 2a_f) \quad (5)$$

However, the distance of two rotors on the counter rotating wind turbine which is designed in this study, is 0.7 m. Therefore it is difficult to see that the rear rotor is in the fully developed stream tube. As the assumption, it is possible that the aerodynamic performance is under-predicted. For solving this problem, BEMT method is validated by the inflow condition of the Vortex Lattice Method(VLM)[9] as shown Fig. 1. However, VLM is not suitable for the optimization process because of the high computing cost. So the BEMT method is still effective.

$$U_{\infty,r} = U_{\infty}(1 - 1.6a_f) \quad (6)$$

Based on the mass-conserving boundary condition, the degree of expansion which is influenced by the wake of the front rotor at the rear rotor is shown below.

$$R_e = R_f\sqrt{(1 - a_f)/(1 - 1.6a_f)} \quad (7)$$

2.2. Optimizing method

For the optimization, the multi-island genetic algorithm(MIGA) is used. MIGA divides population into several islands and traditional genetic operation are performed on each island as shown Fig. 2 and 3. And individual between the islands is migrated for a finding global solution. This method has a low possibility of a deriving a local solution.

For optimizing the maximum efficiency of the power, the chord length and the twist of two rotors, the rotational speed of two rotors and the radius of the front rotor are selected for design values. For simultaneous rotating of two rotors, the solidity ratio of the front and the rear rotor and the torque equilibrium are selected for constraints.

3. RESULT AND DISCUSSION

The validation of BEMT is carried out using vehicle test as shown Fig. 4. The vehicle which was used on test is shown Fig. 5. An anemometer is installed under the one rear rotor radius from the hub. A sampling frequency of the vehicle test is 1 second and the mean values which are averaged over 10 seconds are used.

The blue line is the result of BEMT. But generating efficiency is not considered in this result. Red line is obtained by multiplying BEMT result by the generating efficiency at the rated wind speed. The power is over-predicted at low wind speed regions because the information of the generating efficiency does not exist at this region. The generating efficiency at the rated wind speed is used at the overall region. In the most of cases, the generating efficiency at the low wind speed is lower than the generating efficiency at the rated wind speed. As a result, the prediction of BEMT will close the experimental result. If the consideration is accepted, BEMT show the reasonable prediction.

To optimize the blade, the model of the vehicle test is selected for a baseline. Rotors of this model have a high pitch angle for simultaneous rotating of each rotor. As a result, the baseline has a significantly low power coefficient and long radius of the rear rotor to recover a power loss. The reason is that the solidity of the rear rotor is significantly lower than front rotor shown as table 1. So the solidity must be considered.

The objective function is the maximum power efficiency over than 0.45 for a 600W counter rotating wind turbine. To obtain this efficiency and be suitable for a small wind turbine, the rated wind speed decrease from 9 to 8 m/s and the rear rotor radius decreases from 1.42 to 1.24 m.

After the optimization process, the counter rotating wind turbine whose the maximum power efficiency is 0.47 is obtained. The generating efficiency is not considered at this result. Also the solidity ratio of the rear rotor which is slightly higher than the front rotor is obtained shown as table 2.

Fig. 5 is the power curve of the optimized model. This model is predicted to generate 600W at 8 m/s. The maximum power efficiency considering generator efficiency is 0.4 at rated wind speed. The torque ratio is nearly zero at the overall region. Compared with baseline, the power efficiency of this model is advanced significantly.

4. CONCLUSION

In this study, a blade element & momentum theory of a counter rotating wind turbine for the optimization was developed.

The developed method was validated by comparison with a power curve from the field test on the vehicle. And the prediction has a reasonable performance.

The optimization process for a counter rotating wind turbine was established. The torque equilibrium and the solidity ratio are considered for a simultaneous rotating operation. And the rear rotor radius and the rated wind speed decrease for widely using a small wind turbine. The optimized counter rotating wind turbine design is obtained satisfying the objective function and constraints.

ACKNOWLEDGEMENT

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FIGURE CAPTIONS

Fig. 1. Flow model for BEMT analysis of counter rotating wind turbine corrected by VLM

Fig. 2. Multi-island genetic algorithm

Fig. 3. Flow chart of optimization

Fig. 4. Power curve of vehicle test

Fig. 5. Power curve for optimization

TABLE CAPTIONS

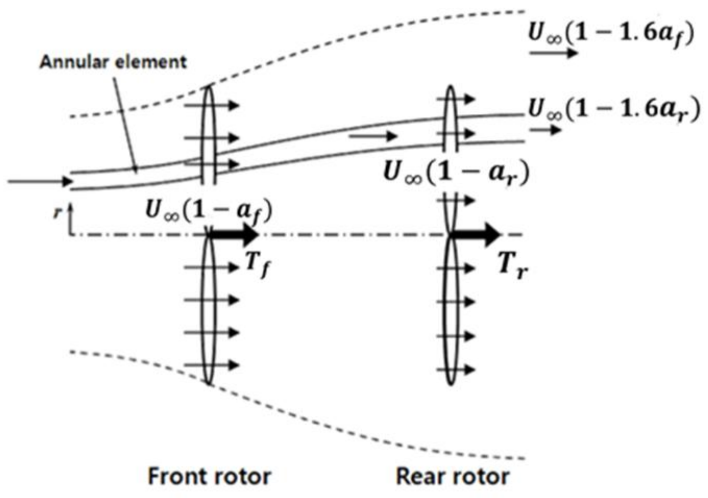

Fig. 3. Flow model for BEMT analysis of counter rotating wind turbine corrected by VLM

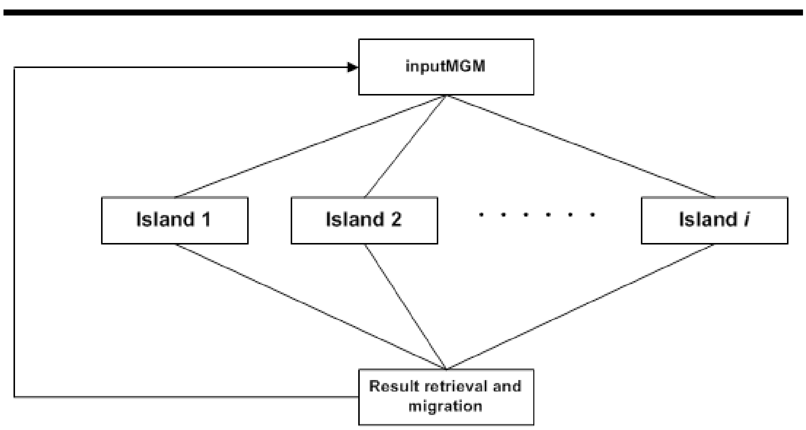

Fig. 4. Multi-island genetic algorithm

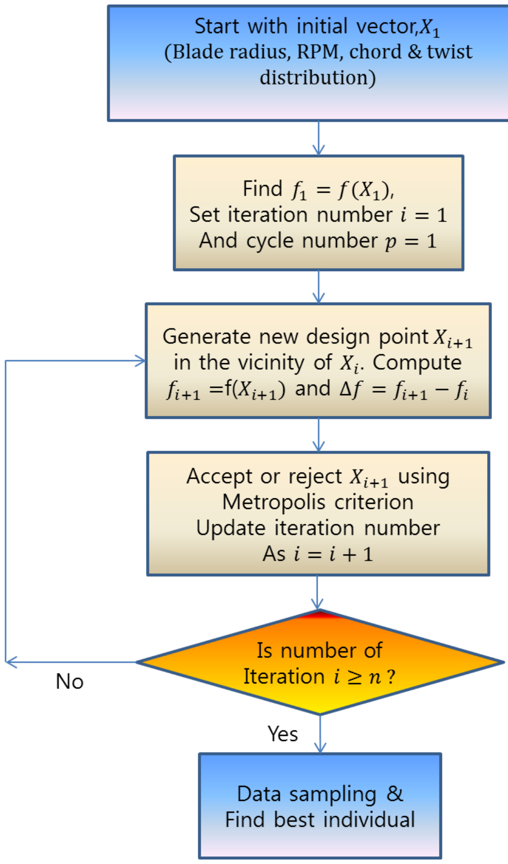

Fig. 3. Flow chart of optimization

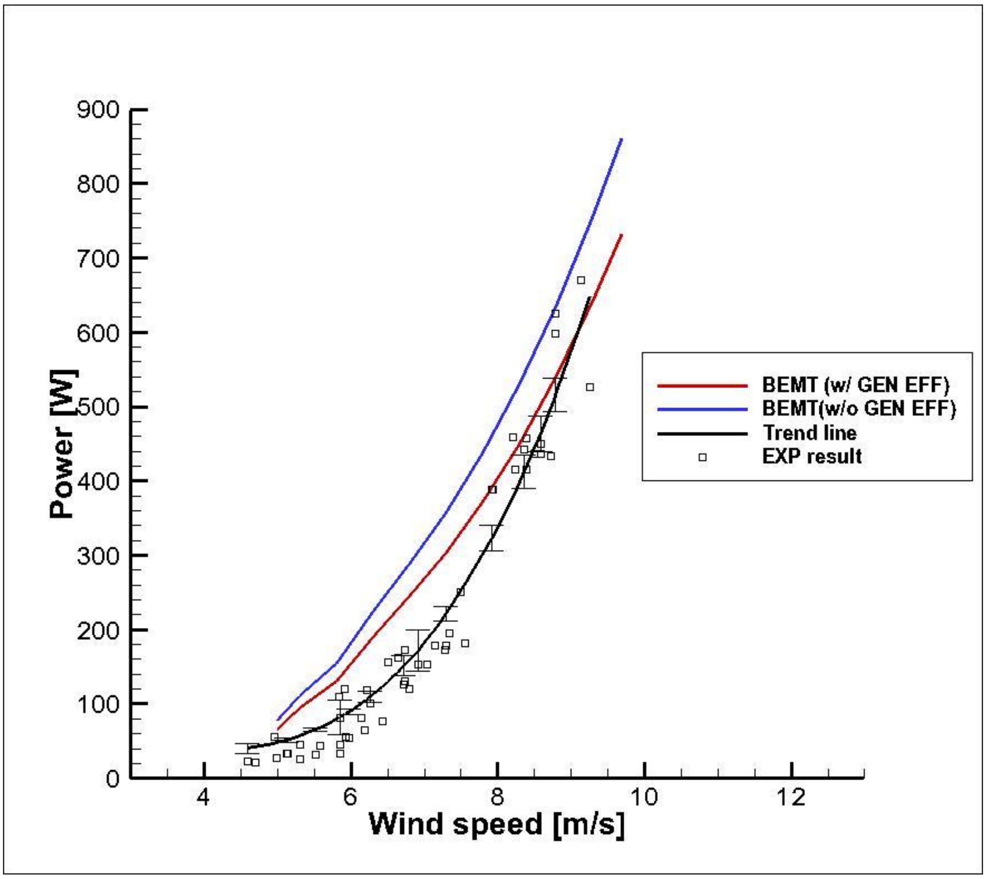

Fig. 4. Power curve of vehicle test

Fig. 5. Experimental equipment of vehicle test

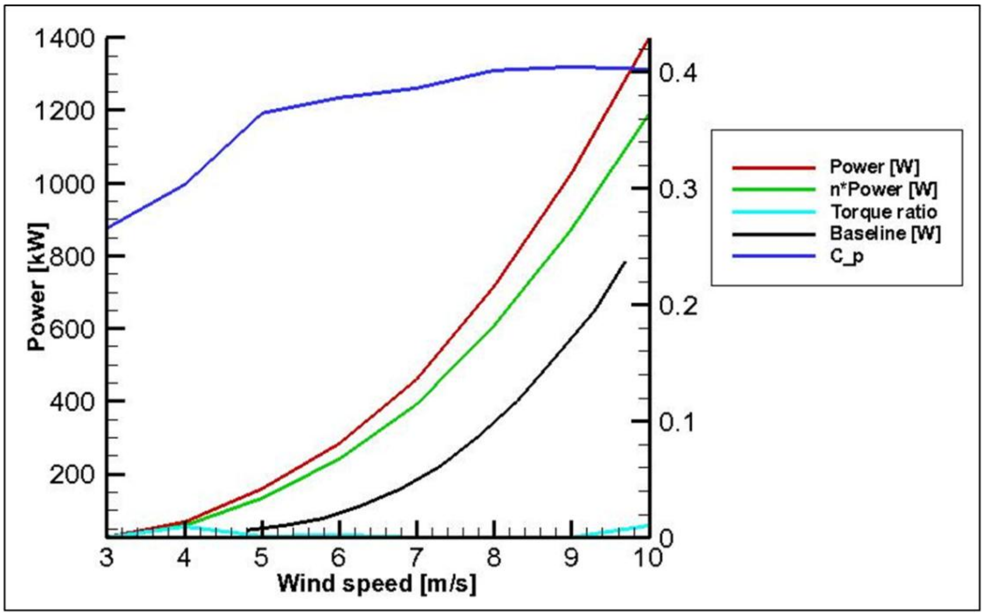

Fig. 6. Power curve for optimization

Table 3. Performance of Baseline

	Front Blade	Rear Blade
Radius [m]	1.07	1.42
Solidity	0.0741	0.0492
Rated speed [m/s]	9	
Power coefficient	0.21	

Table 4. Performance of Optimized model

	Front Blade	Rear Blade
Radius [m]	1.11	1.24
Solidity	0.0792	0.0871
Rated speed [m/s]	8	
Power coefficient	0.47	