A Feasibility Study on High-altitude Wind Power Generation

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1. Background

Wind energy potential studies show that the world-wide wind resources are abundant, and wind power is green renewable energy which is a good solution to mitigate green-house effect and energy crisis. But it is an undisputed fact that ground-based wind power extraction systems have reached their maximum capability and the problem of wind energy intermittency still exists which has negative impacts on existing transmission grid system. Under these circumstances, high altitude wind power generations could be effective alternatives to land-based wind power generations in that wind at high altitude is more powerful and steady than that near ground and thus high altitude wind power generations may solve the problem of capacity and intermittency of conventional wind power generations with less environmental impacts.

2. Objectives

The objective of the present research is to conduct feasibility study on high altitude wind power generations. Especially on an innovative design which generates extra lift and reduces resistance, and mitigate tether drag and space limitation, which may enable the utilization of stronger wind energy at higher altitude.

3. Methodology

3.1 Airfoil contours

As a high-altitude wind turbine, we consider a hollow cylindrical shell structure with rotating blades in it. We design the shell structure whose cross section has geometry of conventional airfoil contours so that a high lift with low drag force is obtained. When an airfoil is moved through an air, a stream of air flow is induced around the airfoil. If the airfoil is set at proper angle of attack (AOA) and the air flow has sufficient velocity, enough lift will be produced to sustain the heavier-than-air craft in flight. The lift of an airfoil can be estimated by the following equation:

$$L = 1/2 C_L \rho V^2 S \quad (1)$$

L $C_L \rho$V and S are lift, lift coefficient, air density, relative airflow velocity, airfoil area, respectively. Proper profile of an airfoil which fits for target altitude wind velocity was

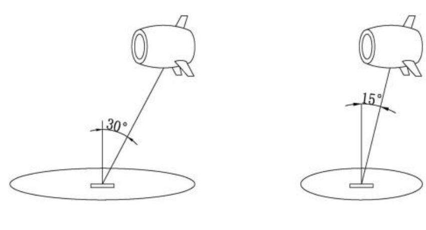


Fig.1 The aircraft will occupy less space by increasing lift and decreasing inclination angle

chosen as the contour of the helium-filled shell, which will produce considerable extra lift and reduce the space occupied by a wind turbine as shown in Fig.1.

3.2 Cross section of the windmill shell structure

The research target altitude is 500~1000 meters high. At that altitude, wind velocity reaches 10~20 m/s. Some airfoils' profile was used as the cross section of a shell structure. For example, as shown in Fig.2, a prototype of windmill which has a cross-section of NACA2412 airfoil profile was chosen as it works with relatively high efficiency at that velocity. Besides, the windmills designed by NACA2411, NACA4412, and NACA6409 airfoil profiles werealso subjected to the simulation.

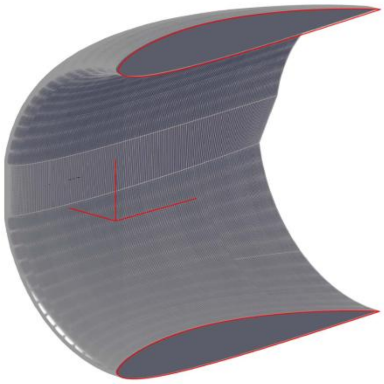


Fig.2The windmilldesign by NACA2412 airfoil profile

3.3 Windmill with a wind turbine in it

In the research, for more realistic simulation, a circular baffle with punch holes to simulate a wind turbine was put in existed windmill design. Based on Betz' law, wind turbines were replaced in the simulations with perforated circular baffles. Four kinds of turbinesof area rate24%, 50%, 54%, 80% representing different power-coefficient wind turbines were subjected to the simulations (the max power coefficient turbine corresponds to 83% area rate). Fig.3illustratesa windmill design by NACA2412 airfoil profile with inner wind turbine (50% area rate).Area rate is defined as the ratio of the actual area of the perforated circular baffle to that of the circle.

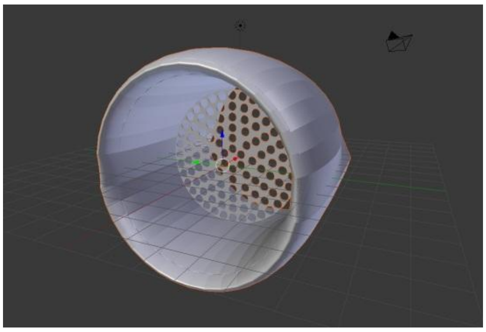


Fig.3 The windmilldesign by NACA2412 with turbine (50% area rate)

4. Numerical simulation

OpenFOAM was used to numerically evaluate the hydrodynamic performance of the designed shell structure. A solver SimpleFOAM was used to solve the flow field around the structure. The governing equations solved are:

$$\frac{\partial u_i}{\partial x_i} = 0 \quad (2) \quad \frac{\partial (u_i u_j)}{\partial x_j} = -\frac{1}{\rho}\frac{\partial p}{\partial u_i} + \frac{\partial}{\partial x_j}\left\{(v_0 + v_t)\frac{\partial u_i}{\partial u_j}\right\} \quad (3)$$

Here, v_0 is a coefficient of kinematic viscosity, and v_t is a coefficient of eddy viscosity. Pressures and velocities around the structure obtained by the numerical simulation were post-processed to get lift force and other data.

4.1 Calculation of a traditional windmill and a new windmill

Other than the new windmill designed by NACA2412 airfoil profile, atraditional windmill was created for comparison, which has a cross-section ofsymmetric streamlinedprofile. No turbines were put in the windmills. Fig.4 shows the drag and lift forces acting on the traditional and the new windmill at 0, 2 and 4 degree angle of attack.

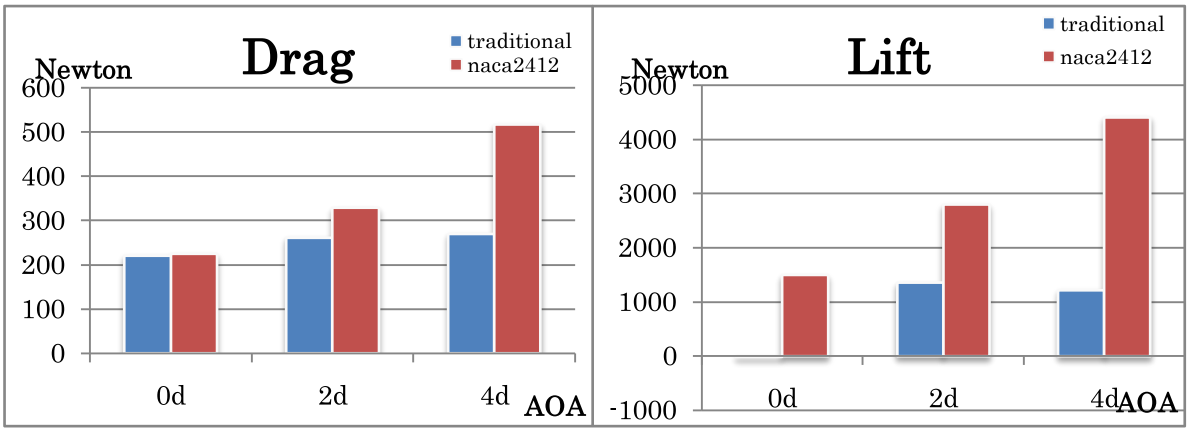


Fig.4 Comparisons of the drag and lift forces acting on the traditional and new windmills at different angles of attack

Fig.5 shows the drag and lift forces acting on the windmillswith inner turbines.

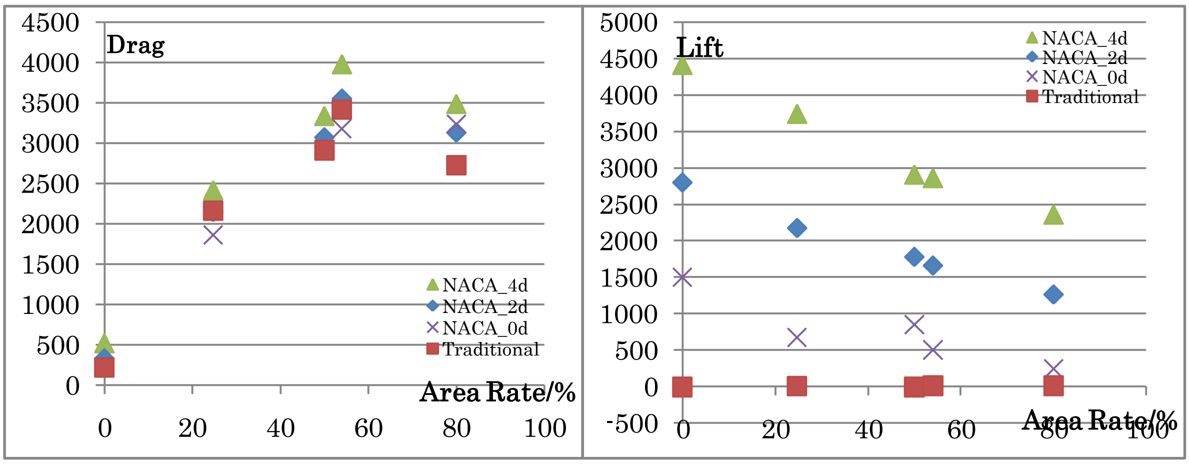


Fig.5 Drag and lift forces acting on the windmills with turbines in them (traditional and new design)

4.2 Calculation of other designs

According to the results shown in 4.1, the windmill designed by NACA2412 generates lift and it increases with angle of attack. But with the increasing of AOA, the drag increases at the same time. In order to explore more efficient design which has a higher ratio of C_L/C_D at small angle of attack, three other kinds of airfoils, NACA2411, NACA4412, NACA6409, were subjected to the simulations, because they are known to show maximum value of C_L/C_Dat relatively small AOA. Figures 6,7,8below show simulation results for lift and drag forces.The inclination angle of the windmills and the radius of occupied area were also calculated to evaluate the windmills' performance for occupied space mitigation.

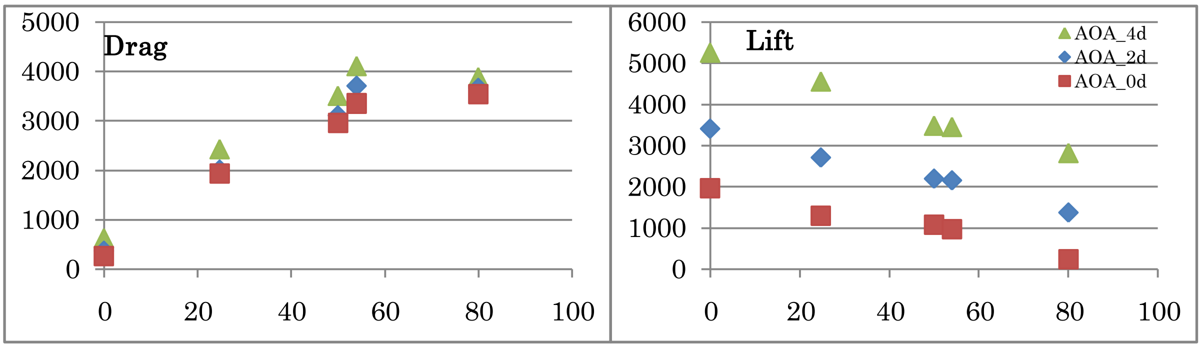


Fig.6 The drag and lift of a windmill with turbines at different AOA (NACA2411)

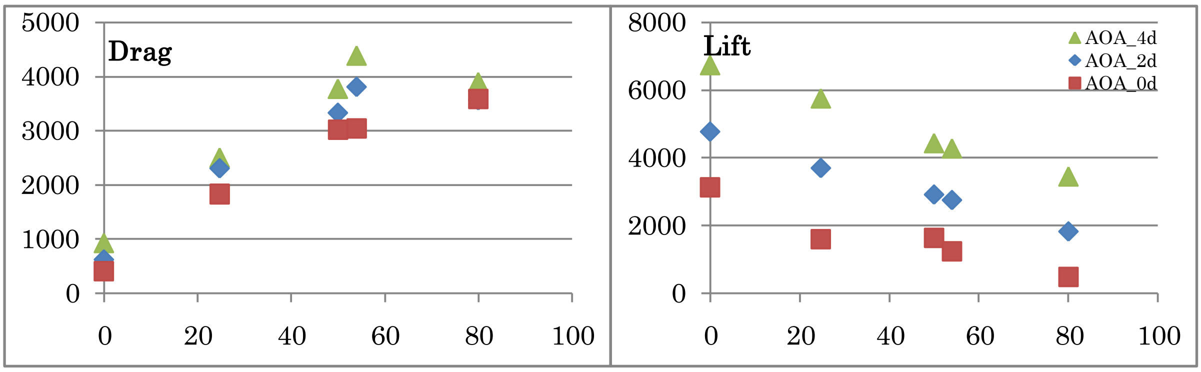


Fig.7 The drag and lift of windmill with turbines at different AOA (NACA4412)

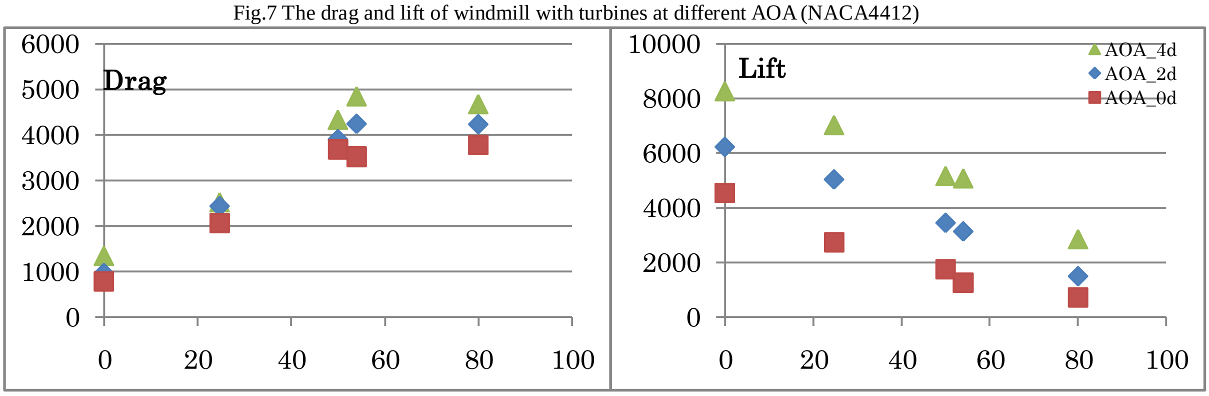
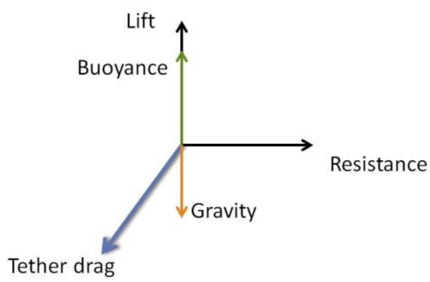


Fig.8 The drag and lift of windmill with turbines at different AOA (NACA6409)

5. Conclusion

From above simulation analyses, it can be concluded that the new designs presented have positive effect on increasing lift and reducing drag.It has also been found that a windmill witha turbine of higherpower coefficient suffers a largerdrag with smaller lift. The inclination angle of windmill and thus the occupied area can be computed by the relations of forces acting on the windmill. Within the windmills examined in the present study, the windmill designed by NACA2412 airfoil profile at 0° AOA showed the best performance for space reduction while its turbine on standby.



When the turbineis at work with75% max power coefficient, the results showed the windmill designed by NACA4412 at 4° AOA has higher efficiency of space mitigation.