Development and performance evaluation of stall delay bi-directional air turbine with additional blades

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Abstract. In this study, we aim to solve the problem of the stall phenomenon on Wells turbines by attaching additional blades to both sides of the rotor surface of Wells turbine. With this new turbine concept, a highly efficient and inexpensive stall delay turbine that can achieve stable efficiency over a wide range of rotation speed. In this abstract, the airfoil and rotor design of the turbine was done using RANS simulation using k-ω SST model. First, a CFD analysis is carried out for a conventional Wells turbine in order to understand the flow field under stall and non-stall region. Based on this result, the blade shape which prevents the torque reduction in the stall region was obtained by two-dimensional analysis and optimization of the turbine cascade. Then three-dimensional turbine performance was evaluated based on the optimized two-dimensional shape. Moreover, we improved the design of the turbine considering three-dimensional effects by changing the height of the additional blade and changing the radial distribution of the blade solidity. The turbine is tested at the real sea test site of OWC plant and compared with traditional Wells turbine.

1. Introduction
The oscillating water column (OWC) wave energy converter is one of the most reliable and promising wave energy conversion systems. OWC converts wave oscillation energy to a bi-directional airflow. To obtain mechanical power from the bi-directional air-flow, bi-directional air turbines are widely used. Amongst the bi-directional air turbines, The Wells turbine is a widely used and the simplest type of air turbine which is deployed in many applications of real-sea test. The efficiency of the Wells turbine is not as high as other turbines for electrical generators because it needs symmetric geometry. In the studies on rotor types, Kaneko et al. [1] conducted a model test on biplane rotor equipped with multiple Wells turbine rotors on the same shaft. They demonstrated that, despite slightly lower efficiency than those of monoplane rotor, an improved operating range of such biplane rotor can be expected. In the studies on the setting angle, Inoue et al. [2] proposed a turbine with self-pitch-controlled blades with the setting angle being automatically reversed by waves, thereby demonstrating a possible improvement of blade starting characteristic. Setoguchi et al.[3] later proposed a turbine equipped with a staggered angle designed to accommodate the difference of the maximum velocity of the oscillating airflow (blowout and suction). They then demonstrated that, with a slight setting angle when there is a large difference of velocity between blowout and suction, both maximum efficiency and operating range can be improved, compared to a setting angle of 0 degrees. In previous research, improved efficiency is achieved with certain significant level. However it is necessary for all
the Wells turbine type turbines to maintain extremely high rotation speed under high input air power in order not to fall into stall region and consequent degradation of the performance. This high-speed characteristic enables direct drive generator without any gearbox even with a large turbine design above 1m diameter. However, careful mechanical, electrical and control design is needed when Wells turbine is deployed.

In this study, we aim to solve the problem of the stall phenomenon on Wells turbines by attaching additional blades to both sides of the rotor surface of Wells turbine. With this new turbine concept, a highly efficient and inexpensive stall delay turbine that can achieve stable efficiency over a wide range of rotation speed. In this abstract, the design concept of the stall delayed turbine, performance prediction by computational fluid dynamics (CFD) analysis and performance evaluation result by field test are presented.

First, a CFD analysis is carried out for a conventional Wells turbine in order to understand the flow field under stall and non-stall region. Based on this result, the blade shape which prevents the torque reduction in the stall region was obtained by two-dimensional analysis and optimization of the turbine cascade. Then three-dimensional turbine performance was evaluated based on the optimized two-dimensional shape. Analytical results of three dimensional performance revealed that with the designed stall delay turbine, the performance dropped considerably due to three dimensional flow, for example the leakage flow of the additional blade tip and the occurrence of the secondary flow due to the increased solidity. In order to solve these problems, we designed a stall delay turbine considering three dimensional effects by changing the height of the additional blade and changing the radial distribution of the blade solidity.

2. Flow simulation method

In the latter of this abstract, A commercial code, Starccm+ ver7.06.012, was used in the numerical analysis. The flow field was assumed to be steady and incompressible. The Navier–Stokes equations governing transport of mass and momentum were solved by the finite-volume method. The second order accuracy upwind difference scheme was used for the convection term, and the turbulence was modelled with the low Re number SST k-ω model to precisely analyse air streams around the blade. The rotating frame of reference of the turbine was adopted. On the upstream boundary, the inlet axial velocity was given, and the static pressure was given on the downstream boundary. No-slip wall conditions were used for the hub surface, blades surfaces and the casing surface. In two-dimensional analysis, slip wall conditions were given the diametrical boundaries. Geometrical layout of computational domain is shown in Figure 1.
3. Investigation of flow field around Wells turbine

Before studying the concept of stall prevention wing, flow analysis of conventional Wells turbine was carried out for the purpose of understanding flow field around stalled Wells turbine blades.

3.1. Model Description

Figure 2 shows simulated Wells turbine model. Specifications are shown in Table 1. This turbine geometry is used in previous open sea trial of floating OWC plant “Mighty Whale”[4] in Japan.

![Simulated Wells turbine](image)

Table 1 Specifications of simulated Wells turbine

| Specification          | Value  |
|------------------------|--------|
| Airfoil                | NACA0021 |
| Diameter [mm]          | 298    |
| Chord length [mm]      | 75     |
| Hub diameter [mm]      | 210    |
| Solidity at blade tip  | 0.64   |
| Number of blades       | 8      |
| Tip gap [mm]           | 1      |

3.2. Simulation accuracy

To evaluate the turbine, below parameters are used. $\phi$ is flow coefficient which represent the angle of attack of the turbine, $C_t$ is torque coefficient, $C_p$ is pressure coefficient and $\eta$ is turbine efficiency.

\[ \phi = \frac{r \omega}{V_x} \]  
\[ C_a(\phi) = \frac{\Delta p}{0.5 \rho_a (V_x^2 + (r \omega)^2)} \]  
\[ C_t(\phi) = \frac{T_t \omega}{0.5 A \rho_a r (V_x^2 + (r \omega)^2)} \]  
\[ \eta = \frac{\frac{T_t \omega}{C_a(\phi) \phi}}{\frac{\Delta p A V_x}{C_a(\phi) \phi}} \]

$r$[m] is tip radius, $\omega$[rad/s] is rotational speed, $V_x$[m/s] is inflow velocity, $\Delta p$[Pa] is turbine pressure drop, $\rho_a$ is air density, $A$[m$^2$] is turbine cross sectional area and $T_t$[Nm] is turbine torque.

As can be seen from Figure 3, the flow coefficient at which the turbine torque characteristic of Wells turbine suddenly falls (stalls) is well reproduced by the simulation. The difference between wind tunnel test and the analysis at the maximum efficiency point was less than 3% of wind tunnel test result. Therefore, it is confirmed that the simulation has accuracy enough to discuss stall phenomenon and turbine performance.
3.3. Flow field around typical Wells turbine

Figure 4 shows the streamline from the leading edge of the turbine. From the pattern before stall, it can be seen that the wake of the leading blade suppresses the flow separation of the rear blade at maximum efficiency point. Therefore, it can be said that there is a strong correlation between wake of the leading blade and the turbine characteristics. At highest torque point close to the stall point, the less interaction is seen but the flow around the blade is still attached to the turbine surface. However, after the stall a huge separation occurs from the root to the tip of the rear blade therefore huge drop of the torque occurs.

4. Development of Stall delay turbine

4.1. Concept of new stall delay turbine

From the above simulation results, it is suggested that Wells turbine is structured so that its symmetrical blades are installed at a setting angle of 0 degrees, and that the both leading edge and trailing edge are
at the same location axially, so that wake from the leading blade largely contributes to turbine performance (turbine efficiency and the stall region). We then proposed “Stall delay turbine”, that basically consists of the airfoil profile that achieves higher performance over a wide operating range as shown in Figure 5

Figure 5 Airfoil cascade of stall delay turbine

4.2. 2D optimization of the airfoil cascade

The new designed air turbine equipped with additional blades aims to delay stalls and highly circulate the flows around the blades by using wake from the additional blade. In these effects, two-dimensional flows are presumably dominant. We then verified the effects of enhanced performance of the air turbine with additional blades by two-dimensional simulation. Figure 6 shows the design factors of the main blade and additional blades. Table 2 lists the level range and optimal values of the design factors. As a method of optimizing the airfoil profile of the blades of the proposed stall-delay turbine, we used the response surface methodology based on the RBF (Radial Basis Function) network and the PSO (Particle Swarm Optimization) algorithm, in order to explore the global optimal solutions. The samples required for response surface plotting were based on LHD (Latin Hypercube Design) so as to arrange samples throughout the design variables. Optimization by PSO was calculated that maximizes turbine efficiency (objective function) as constrained by stall-delay. Optimization target is turbine efficiency at $\phi =0.135$, constraint for optimization is that torque coefficient should not be below that of Wells turbine and its extrapolated torque coefficient after stall. described above, based on the results of two-dimensional simulation on the airfoil profile of 40 blade samples.

Table 2 List and range of optimum parameters for 2D airfoil design

| Design factor             | Range          |
|---------------------------|----------------|
|                           | Minimum        | Maximum       |
| Main blade                |                |               |
| Thickness c [-]           | NACA0012       | NACA0024      |
| Maximum thickness position t [%] | 15             | 30            |
| Solidity σ [-]            | 0.55           | 0.75          |
| Additional blade          |                |               |
| Leading edge distance x [mm] | 0              | 30            |
| Trailing edge distance r [mm] | 105            | 125           |
| Trailing edge position $\theta$ [deg] | 12             | 25            |
| Leading edge angle $\alpha$ [deg] | 15             | 35            |
| Trailing edge angle $\beta$ [deg] | 0              | 12            |
| Leading edge radius $R$ [deg] | 2.5            | 4.5           |
Figure 6 Optimum 2D airfoil geometry of the stall delay turbine

Figure 7 shows the characteristics of Wells turbine (Figure 2) and those of the stall delay turbine. It was difficult to improve Wells turbine performance at large flow coefficients where turbine torque has declined quickly due to a stall. Even at those coefficients, it can be seen that the air turbine with additional blades delay stalls where the torque coefficient satisfies the optimization constraints, resulting in wider ranging turbine efficiency. Conversely, maximum efficiency declines compared with Wells turbine. This is because installation of the additional blades increases solidity (from 0.70 to 0.88), resulting in a higher-pressure difference coefficient.

Figure 7  2D performance analysis result of the stall delay turbine (at 70% radial position of the blade)

4.3. 3D performance analysis

The aerodynamic performance of existing Wells turbine and stall delay turbine are shown in Figure 8. The same airfoil shape is used in all radial position of the stall delay turbine likewise Wells turbine in Figure 1. In the existing Wells turbine, the turbine torque coefficient drops due to the stall at the large flow coefficient ($\phi > 0.33$), but in the stall delayed turbine, the turbine torque coefficient is not dropped as shown in 2D analysis. However, a reduction of turbine torque and an increase in turbine differential pressure compared with the existing Wells turbine, and consequent the turbine efficiency was inferior to the existing Wells turbine were observed in the low flow coefficient ($\phi < 0.33$).
5. Improvement design including 3D effect

5.1. Concept of 3D performance improvement

In order to consider the reason and methods to improve the inferior performance of the stall delay turbine shown in Figure 8, streamline around the stall delay turbine from 3D analysis is shown in Figure 9. From Figure 9, it became clear that a large loss occurred due to the tip leakage flow and the blade tip leakage vortex of the main blade’s suction surface. That phenomenon cannot be predicted by 2D analysis used for turbine cascade design. Therefore, the geometry of the turbine is modified to improve the performance as shown in Table 3. The resultant geometry is shown in Figure 10. Additional blade is ended at 90% of the spanwise position.

![Figure 9 Streamline around stall delay turbine.](image)

Table 3 Concept of 3D performance improvement

| Problems found from 2D optimum rotor | Solution | Resultant change of the geometry |
|--------------------------------------|----------|----------------------------------|
| Radial flow on the pressure side of main blade | Lead the wake to the suction side | Reduce the overlap of the main and additional blade by reduce the chord length of the additional blade at the root |
| Tip leakage vortex of the main blade | Lead the leakage flow to the rotational direction | Reduce the height of the additional blade |
|                                       | Reduce the tip vortex from the main blade | Reduce the tip gap of the main blade |
The air velocity and pressure distribution around the blade at each span wise cross section of the 2D optimum stall delay turbine and the improved stall delay turbine at maximum power point of the existing Wells turbine (φ = 0.19) are shown in Figure 11. In addition, the results of the two-dimensional analysis shown in Figure 7 is shown atop the 3D result. In the stall delay turbine using the two-dimensional shape (left in the figure), there is a large separation of the suction surface which is not observed in the two-dimensional analysis result, but with the improved stall delay turbine (right in the figure), prevention of large separation has been realized and the result of the improved design is close to the result of 2D analysis. However, as compared with the two-dimensional turbine, the wind speed around the downstream side additional blade is small. In other word, Optimum flow condition which predicted by 2D analysis has not yet realized. Therefore, there is room for further improvement in efficiency.

Figure 12 shows the performance of the improved stall delay turbine considering the three-dimensional effect and the performance curves of three types of turbines, stall delay turbine and wells turbine before improvement. As can be confirmed from the figure, the performance to kick into the efficiency point improved by changing the shape taking the 3-dimensional effect into account. However, it is thought that the efficiency decreased due to the increase of the drag force and differential pressure caused by the additional blade.

6. Result from the field test

The designed turbine was subjected to a performance test at the OWC wave power test plant in Fukui prefecture[6]. Both the improved stall delay turbine and Wells turbine were made with a diameter of 460 mm and were tested using two primary conversion section with a width of 1.4 m and a generator with a power of 15 kW. Primary conversion sections for each turbine are parallelly equipped with distance of 1.4m. Because of the distance is small, we assumed the input wave condition is almost same to each primary conversion section.

10 minutes average time series of the rotational speed and significant wave height measured 200m ahead of the wave energy converter is shown in Figure 13. As is clear from the result, the stall delay turbine shows higher rotational speed at which Wells turbine shows low speed. One of the reason must be the improved starting performance due to good performance at high flow coefficient (low turbine speed compared with the air velocity) achieved by additional blade of the stall delay turbine.
29th IAHR Symposium on Hydraulic Machinery and Systems  
IOP Conf. Series: Earth and Environmental Science 240 (2019) 052014  
doi:10.1088/1755-1315/240/5/052014

Figure 11 Pressure and velocity around turbine cascade

Figure 12 Performance of the improved stall delay turbine
7. Conclusion
We devised a stalled delay turbine that prevents turbine torque drop due to turbine stall and consequent turbine efficiency drop which was a problem of Wells turbine. The optimization study of the turbine geometry was conducted by simulation. Followings are conclusions.
・ In Wells turbine, its performance (turbine torque and a sharp drop in turbine efficiency) strongly depends on the wake from the leading blade.
・ A stalled delay turbine with additional blades to prevent performance drop of the stall and realize performance improvement of wide range of flow coefficient.
・ 2D airfoil cascade optimization was done by numerical optimization.
・ 3D analysis showed there is a strong 3D performance reduction with stall delay turbine. However, performance improvement is confirmed in the stall region of Wells turbine.
・ Improved stall delay turbine is proposed and showed some improvement in the performance compared with 2D optimum stall delay turbine.
・ Field test showed better starting performance of the improved stall delay turbine compared with traditional Wells turbine.

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