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Numerical Simulation of Unsteady Flow and Aerodynamic Performance of Vertical Axis Wind Turbines with LES

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Abstract

The goal of this investigation is to develop high performance Vertical Axis Wind Turbines (hereafter VAWT) for clean energy supply systems. For this purpose, we attempted to simulate flow around a VAWT with Large Eddy Simulation (LES). Since the angles of attack of VAWT are widely changed during the rotor rotation, large scale separation and interaction between the turbulent wakes are occurred [1]-[3]. Therefore, unsteady and high accuracy simulation is necessary to simulate flow around a VAWT. LES with a sliding mesh technique was utilised to solve the complicated flow around the VAWT. The numerical results show the large separation occurred and unsteady aerodynamic forces were observed in the wake of VAWT. The time ratio of negative torque generated after rotor rotation time was small at a tip-speed ratio (TSR) of 3. Therefore, the maximum power coefficient can be obtained at a TSR of 3. In the case of high TSRs, the predicted results were in good agreement with that of momentum theory. However, the discrepancies among torque coefficient between the results of LES and momentum theory were large at low tip-speed ratios. The discrepancy seems to occur with the effect of dynamic stall. The study revealed that the LES is a suitable method to estimate the performance of VAWT.

Introduction

Darrieus turbines are well known Vertical Axis Wind Turbines with beautiful and unique curved blades, which remove centrifugal force on the blades. Vertical Axis Wind Turbines are one of the useful renewable energy systems. They have several advantages in comparison with conventional, propeller-type, horizontal axis wind turbines [1]. For example, conventional wind turbines have to be set into the wind direction to operate at maximum efficiency; however, VAWT operate independently of the wind direction. Moreover, the maximum power coefficient can be obtained at lower TSR compared to conventional wind turbines. Flow induced noise is therefore less than that of conventional turbines.

Although VAWT have high performance and advantages in comparison with conventional wind turbines, the operations of VAWT are limited to use for laboratory experiments. Or, they are installed in parks as monuments or symbols for renewable energy systems. One of the disadvantages of the VAWT is weak self-starting. In the case of low TSR, the average torque of the turbine is equal to almost zero or sometimes it's negative. Therefore, starting motors or engines are required.

The other problem of the VAWT development is that the effective operation range is small. Although the maximum power coefficient of VAWT is almost the same order as the conventional ones, the band width of the TSR in the effective operation range is too narrow for electric power generators. This disadvantage reduces the net amount of the electricity generation par year.

In order to improve on these disadvantages, we should consider flow fields around a VAWT. However, the flow field around a VAWT is complicated, because of the interactions of the large separated flow and wake itself. The flow field of VAWT is essentially unsteady, turbulent and separated flow. To simulate flow around a VAWT and estimate its aerodynamic performance, numerical flow simulations were carried out. To simulate large separated flow from turbine blades, the sub-grid scale turbulent model was adapted. The sliding mesh technique was also introduced to simulate the rotational blades. The numerical results were compared with the calculated results based on momentum theory.

Numerical Simulation

Wind turbine

Figure 1 shows the straight-winged vertical axis wind turbine, which has been developed by the authors. This wind turbine has three straight wings. The shape of the cross-section of the airfoils is NACA0018. The chord length and spanwise lengths of these airfoils are 300 mm and 2400 mm respectively. The rotor diameter of the turbine is 3600 mm. The blades are mounted on the center pole with six supports. The supports are covered with aerodynamic fairing.

Figure 1 Vertical axis wind turbine with straight airfoils

Figure 2 shows stream lines and a schematic of the top view of the VAWT. The direction of the uniform flow is from the left to the right in this figure. The direction of the rotor rotation is counter-clockwise. The angle of the rotor rotation was measured from the horizontal line of the downstream. To identify the blade, a number was assigned to each blade. In Figure 2, the number 1 blade was set at the rotational angle of 90 degrees. The aerodynamic forces and torque were numerically calculated at each blade. Therefore, the relationship between the torque fluctuation and vortices structure can be considered in this investigation. The stream lines around a VAWT were complicated. This figure shows the flow around a blade; #1 was smooth and no separation occurred. The large separated flow can be seen at the flow around blades #2 and #3. The interaction between the wake of the blades #3 and #2 seemed to have occurred. Moreover, the Karman vortex street can be seen just behind the centre pole. It reduced the aerodynamic performance of the wind turbines. Therefore, the interaction should be removed.

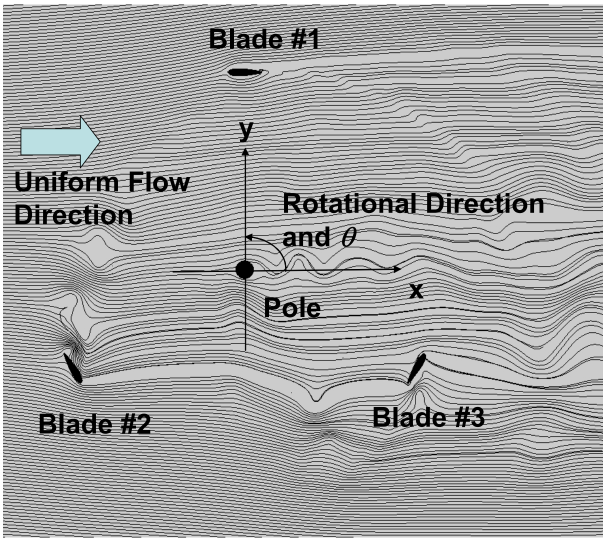

Figure 2 Schematic of Vertical Axis Wind Turbine and stream lines

Numerical Method

To solve the large separated unsteady-flow [1][2], numerical simulations were conducted utilising an incompressible Navier-Stokes equation and the sub-grid scale model for turbulence [4]. The standard Smagorinsky model was adapted as the sub-grid scale model for turbulence. The Van-Driesr wall-damping function is also used for modelling near-wall effects. The Smagorinsky constant is fixed to 0.15 and the grid-filler size is computed as the cube-root of the volume of each finite element.

To simulate moving airfoils, a sliding mesh technique was utilised. Figure 3 shows the stationary and rotational grids around a VAWT. The computational grid can be divided into three elements; rotational grid, stationary grid and grid for the buffer region (not shown in Figure 3). To reduce the numerical error caused by the outer boundary, the coarse mesh was used for the buffer region of the simulation. The number of buffer region mesh was 105,000.

In this figure, the red line shows the outer boundary of the rotational grid. The rotational grid included airfoils and the centre pole. The shape of the outer boundary was cylindrical and mesh size of the outer boundary was uniform. The number of the grid element was 575,000. The outer element of the stationary grid was placed around the rotational grid. The size of the inner boundary of the stationary grid was equal to that of the outer grid of the rotational grid. The time step of simulation was chosen to vertexes of rotational and stationary mesh was overlap at 6 times the time step. Since the relative positions of each mesh on the boundary were similar, the numerical error caused by mesh deformation was restricted. The number of the stationary grid was 110,000. The total number of mesh was about 790,000.

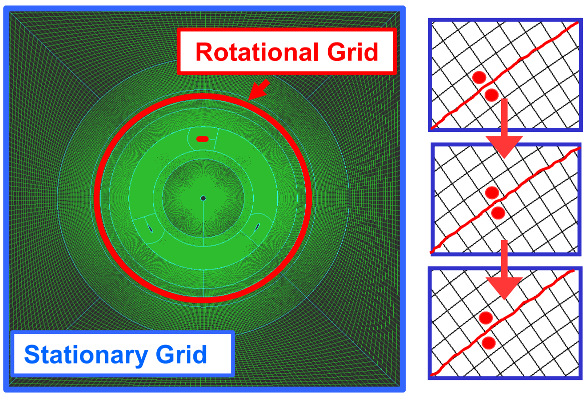

Figure 3 Computational mesh for numerical simulation for VAWT

Numerical Condition

At the upstream boundary of the inlet, a uniform velocity was prescribed. At the downstream boundary, static-pressure was assumed to be zero. On the surface of the blades and the cylinder, a non-slip condition was prescribed. Symmetric boundary condition was used for both sides of spanwise direction. The distance of spanwise direction is equal to 0.25 times the chord length of c. The uniform velocity was 6 m/s and TSR range was set from 2.0 to 6.0. Aerodynamic forces, surface pressure fluctuation, vorticity distributions were estimated.

Numerical Results

An aerodynamic difference between a VAWT and Horizontal Axis Wind Turbine (HAWT) is the appearance of unsteady flow phenomena. During a revolution of the rotor of VAWT in a steady wind stream, the flow direction and velocity relative to the rotor blade varies in a cyclic way. The angle of attack becomes about 180 degrees at off design point (TSR = 2). Therefore, the large separated flow can be seen in Figure 4 (a). The strong interaction between the separated boundary layer and moving airfoils was observed during the rotor rotation. Since there is uniform flow through the blades, the aerodynamic torque generated upstream (at θ = 90 ~ 270 degrees) was larger than that of the downstream torque at the effective operation point. However, the large separation occurred from the blade #2 at low TSR. The aerodynamic thrust force seems to be not so large.

In the case of TSR = 3, separated flow around the blades was restricted. However, the vortices from the blades #3 were still retained. In the case of TSR = 4 and 5, no large separation can be seen in the Figure 4 (c) and (d). In these TSRs, the angle of attack is less than 20 degrees.

Figure 5 shows the distribution of the torque acted on for the each blade. The torque of each blade was almost the same. The maximum torque of TSR = 2 and 4 was generated at θ = 120 degrees and 180 degrees, respectively. The positive torque was mainly generated at the upstream. The width of the positive torque distribution at the low-TSR was narrow and maximum torque was also smaller than that of the high-TSR.

Basically, the efficiency of VAWT depends on the way of the torque magnitude varies throughout the rotation cycle. Since the angles of attacks are wildly changed during the rotation, the torque was also changed from positive to negative. Figure 6 shows the time ratio of the negative torque period to the rotational time. The time ratio depends on the TSR. The minimum value was obtained at TSR = 3. In the case of the large TSR, the maximum torque was increased; however, the time ratio of the negative torque was also increased. This is possibility one of the reasons for the low efficiency of VAWT at the large TSR. The effective TSR was therefore obtained at TSR's around 3 – 4.

Figure 7 shows the power coefficient of the VAWT. The maximum power coefficient was about 0.35 at TSR = 3. After that, the power coefficient rapidly decreased to almost 0 at TSR = 5. At the low tip-speed ratio, the angle of attack was over 20 degrees at every rotating position. The flow separation occurred.

The aerodynamic performances of wind turbines were estimated by the momentum theory combined with blade elements theory [5][6]. In the case of VAWT, rotor blades passed the uniform flow in twice in one revolution. Two actuator disks are necessary to resolve the flow fields. The boundary conditions of the upstream disk are clearly known. However, the boundary conditions of the downstream disk are unclear. It depends on the upstream condition. Thus, some hypothesis or assumptions are required to determine the boundary conditions for the two actuator disks of VAWT. The performance of the conventional, propeller-type wind turbines can be estimated and determined by the momentum analyses. However, the performance and the fine detail of the flow fields are not simulated. Then the aerodynamic modifications are not progress in VAWT developments.

In Figure 7, the solid line shows the power coefficient estimated by the momentum theory. The results indicate that the at high TSR region (including the effective TSR) the estimated power coefficient calculated by the momentum theory was in good agreement with the results of the numerical simulation. In this case, divergence flow and dynamic stall were not considered. Therefore, an unsteady phenomenon was not so important at high TSR. On the other hand, the power coefficient was negative at low TSR estimated by the momentum theory. The results of LES at low TSR, show the power coefficient was still positive. The self-starting is one of the disadvantages of the VAWT. However, in our experiment, when the generator load was removed at the stationary condition, VAWT can be rotated itself. Therefore, the negative power coefficient seems to be incorrect. Thus, the LES result was in reasonable agreement with the experimental result.

Figure 8 shows a comparison of the estimated torque with LES and momentum theory. In the case of high TSR, torque estimated from the momentum theory was almost the same as that of LES. On the other hand, the LES at low TSR is not congruent with that calculated from momentum theory. This large discrepancy becomes the effect of dynamic stall on the moving airfoils. The LES result showed that the torque was positive at θ = 120 -210 degrees. Basically, the divergence flow increases the angle of attack of the blade. As a result, the divergence flow reduces the power coefficient at low TSR. The present estimation using the momentum theory was not considered to be the result of dynamic stall and divergence flow. Large Eddy Simulation considered divergence and dynamic stall. Therefore, the effect of divergence flow was weak or negligible. However, the effect of the dynamic stall was large. It indicated that the effect of the dynamic stall is a considerable parameter for the performance estimation of VAWT.

Conclusion

In order to understand the unsteady flow around a VAWT, numerical simulations were conducted with LES. The numerical results showed that the LES results were in good agreement with those of the conventional momentum theory. It indicated that the effect of the divergence flow and dynamic stall was small at high TSR. On the other hand, the effect of dynamic stall becomes large at low TSR.

The time ratio of the negative torque was minimum at TSR = 3. This time ratio increased at high TSR. As a result, the maximum power coefficient was also obtained at TSR = 3.

The absolute torque of high TSR region was large, but the effective or averaged torque becomes small. This is because the power coefficient was reduced at high TSR. The power coefficient was rapidly decreasing in the high TSR region. To improve on this disadvantage, the installation angle should be chosen to reduce the time ratio.

Acknowledgments

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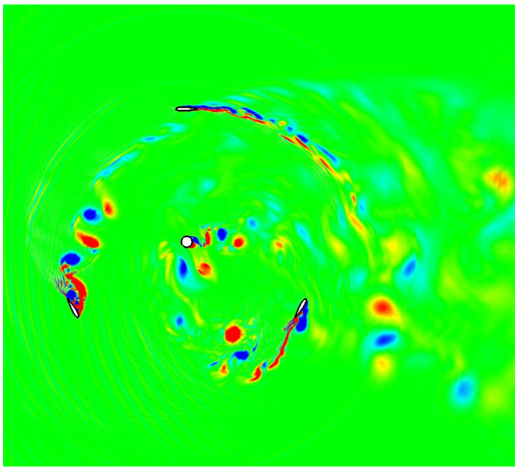
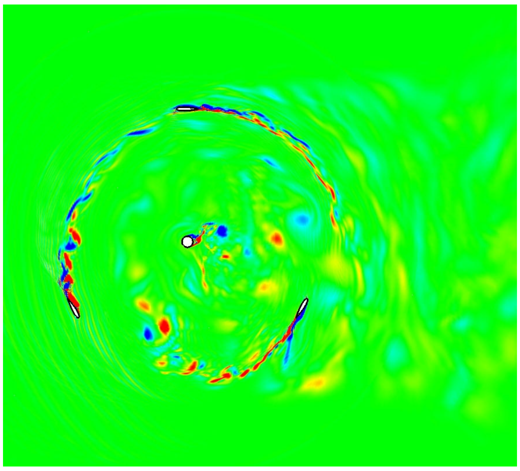
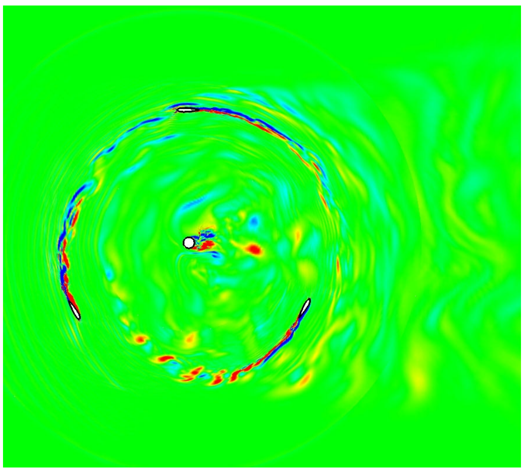


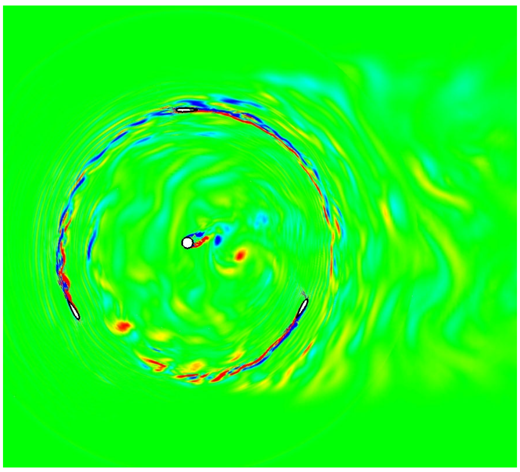
(a) $\lambda = 2$



(b) $\lambda = 3$

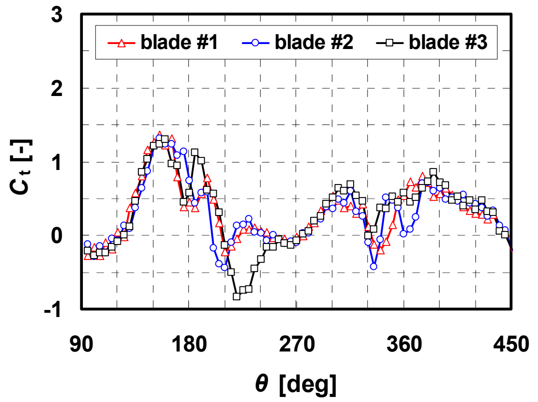


(c) $\lambda = 4$

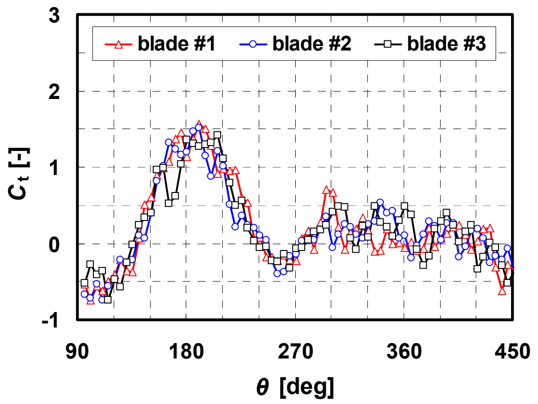


(d) $\lambda = 5$

Figure 4 Vorticity distributions around a VAWT predicted by LES



(a) λ = 2



(b) λ = 4

Figure 5 Phase evolution of torque coefficient of VAWT simulated by LES

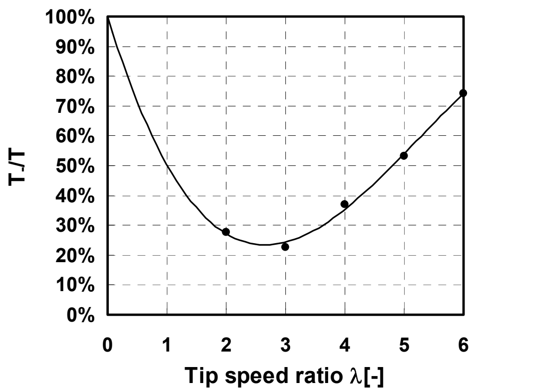


Figure 6 Ratio of negative torque period to rotational time of VAWT

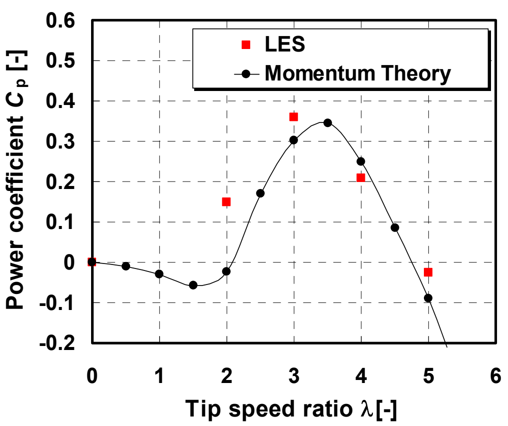
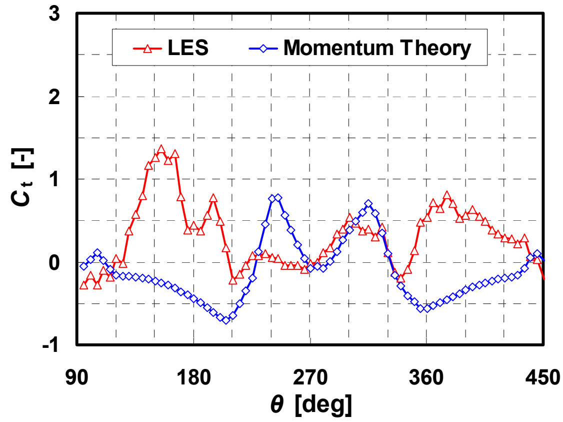
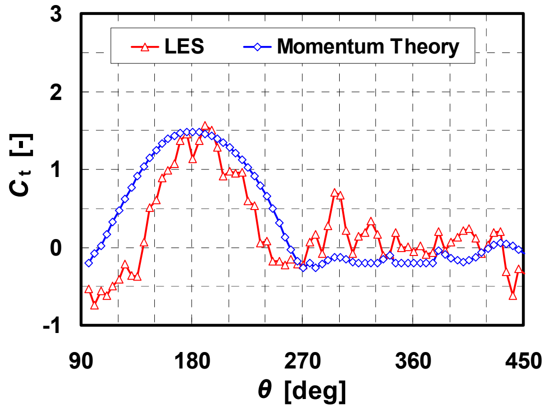


Figure 7 Power coefficient of VAWT



(a) λ = 2



(b) λ = 4

Figure 8 Comparison of estimated torque of LES result and Momentum theory

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