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An Experimental Study of the Shapes of Rotor for Horizontal-Axis Small Wind Turbines

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1. Introduction

Aggravation of the problems of both the environment and the limited fossil energy at present has enabled the wind energy, the limitless source of energy without environmental pollution, to draw a good deal of public attention.
The large-scale wind turbines with the grid connection system operated in wind farms are being used for the power generation in many advanced nations. On the other hand, the small-scale wind turbines have been used as the independent source of electricity regardless of the places. In recent years, these small wind turbines of a diameter under 2m are employed for street lights, park lights, environmental monuments, power sources for emergencies and teaching materials. Because such small wind turbines are usually installed in urban areas, the noise generate from rotor, the failures due to the sudden changes of the wind direction and wind speed which are peculiar to those areas became particularly noticeable these days with increase of the installation.
The rotors for small wind turbines designed to have low tip speed ratio are increasing in number because of their reduced noise. The development of generators and controllers suitable for low rotational speed is largely accelerated these years. While there are many papers on the small wind turbine rotors with high tip speed ratio adjusted for conventional generators, a number of the paper systematically dealing the rotor shapes applied for low tip speed ratio is very small.
In this study, two types of experimental models are prepared to compare the performance at low tip speed. One has a rotor with tapered blades designed by the combined blade element and momentum theory, and the other has a rotor with inversely tapered blades in which the calculated chord lengths are applied in an opposite way.

2. Experimental models

The experimental models were designed according to the combined blade element and momentum theory. The following of equations shows the expressions used for the model design.

Local tip speed ratio: $$\lambda_{rd} = \lambda_d \frac{r}{R} \tag{1}$$

Inflow angle: $$\theta = \frac{2}{3}\tan^{-1}\frac{1}{\lambda_{rd}} \tag{2}$$

Blade pitch angle: $$\beta = \theta - \alpha \tag{3}$$

Blade chord: $$C = \frac{8\pi r}{BC}(1-\cos\phi) \tag{4}$$

B : Number of blades, C : Chord length[m], R : Rotor radius[m], r : Local rotor radius[m], λ_{rd} : Local design tipp speed ratio, λ_d : Design tip speed ratio, θ : Inflow angle, α : Design angle of attack, β : Blade pitch angle

Rotor diameter is 0.6[m] and aerofoils of the blades are all Clark Y. Figure 1 shows the characteristics of Lift on Clark Y. For each tapered and inversely tapered type, we prepared five different shapes of blades. For typical three blade-shapes out of the five of both types, blade numbers are varied from two to six as shown in Table 1 and Table 2, which shows the design values of each model corresponding to the figure 2 to figure 6.

Nominal designations of blades in the table are defined by the authors to distinguish the taper-types and shapes of the blades as follows. “2” in the last digit stands for the normally tapered-blade and “4”, the inversely tapered one. “2” to “4” in the first digit stand for the different tip speed ratio in a five-bladed rotor where the bigger the number, the smaller the chord length. The blades with “5” in the first digit are used in a three-bladed rotor and “6”, in a five-bladed one. The 5xx and 6xx blades are designed to have the same tip speed ratio, λ=3.4.

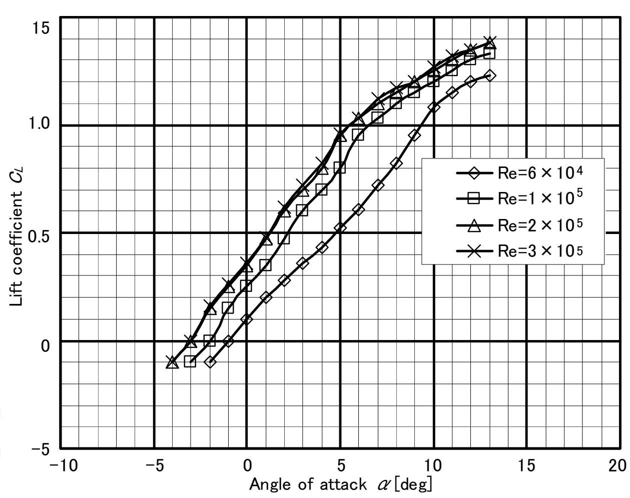


Fig. 1. Characteristics of Lift at Clark Y

Rotor diameter[mm]	600
Aerofoil	CLARK Y
Design lift coefficient	1.1
Design angle of attack[°]	8
Linearization point 1[%]	75
Linearization point 2[%]	95

Table 1. Preliminary design values for experimental models

Blade type No.	202（Tapered）、204（Inversely tapered）				
Number of blades	2	3	4	5	6
Design tip speed ratio	3.4	2.72	2.29	2	1.78
Blade pitch angle at 80% from root[°]	5.6	8.6	11.2	13.4	15.5
Tip chord length of tapered type[mm]	64.4				
Tip chord length of inversely tapered type[mm]	113.3				
Blade type No.	502（Tapered）、504（Inversely tapered）				
Number of blades		3			
Design tip speed ratio		3.4			
Blade pitch angle at 80% from root[°]		5.6			
Tip chord length of tapered type[mm]	40.9				
Tip chord length of inversely tapered type[mm]	84.0				
Blade type No.	302（Tapered）、304（Inversely tapered）				
Number of blades	2	3	4	5	6
Design tip speed ratio	5	4	3.4	3	2.72
Blade pitch angle at 80% from root[°]	1.4	3.7	5.6	7.2	8.6
Tip chord length of tapered type[mm]	22.5				
Tip chord length of inversely tapered type[mm]	38.0				
Blade type No.	602（Tapered）、604（Inversely tapered）				
Number of blades				5	
Design tip speed ratio				3.4	
Blade pitch angle at 80% from root[°]				5.6	
Tip chord length of tapered type[mm]	24.6				
Tip chord length of inversely tapered type[mm]	50.4				
Blade type No.	402（Tapered）、404（Inversely tapered）				
Number of blades	2	3	4	5	6
Design tip speed ratio	6.4	5.2	4.5	4	3.4
Blade pitch angle at 80% from root[°]	-0.6	1.1	2.4	3.7	4.9
Tip chord length of tapered type[mm]	18.0				
Tip chord length of inversely tapered type[mm]	38.0				

Table 2. Design values of each blade for experimental models

Fig. 2. Experimental blades of 202, 204.

Fig. 3. Experimental blades of 502, 504

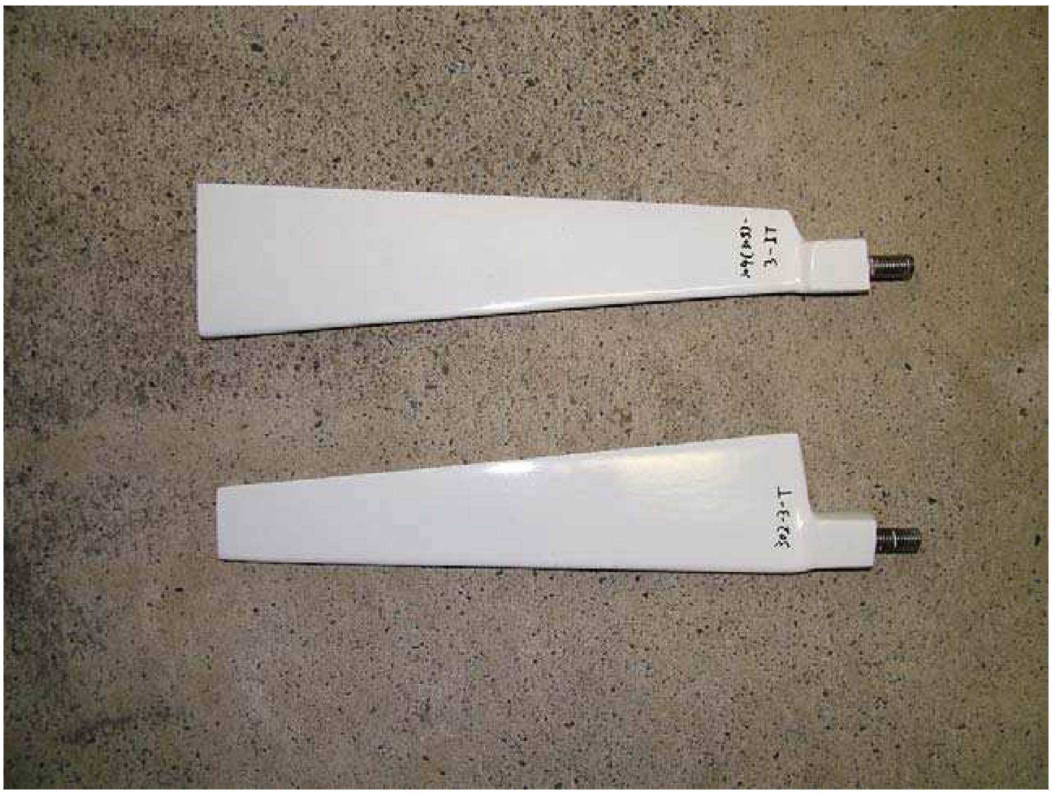


Fig. 4. Experimental blades of 302, 304

Fig. 5. Experimental blades of 602, 604

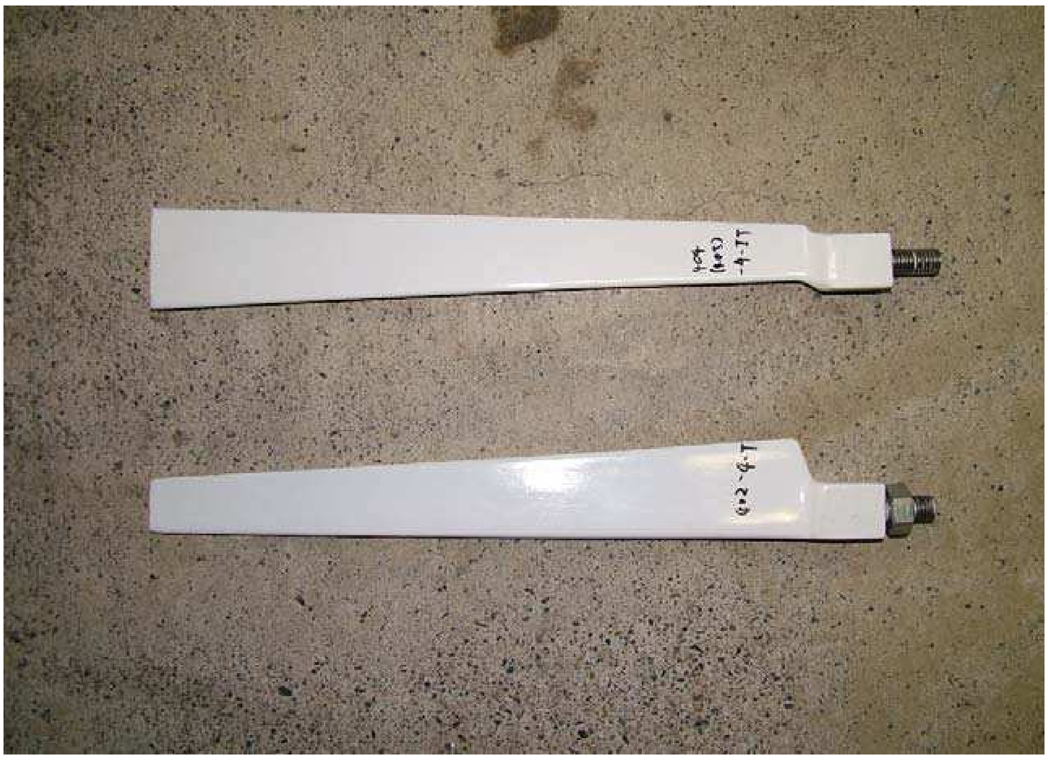


Fig. 6. Experimental blades of 402, 404

3. Experiments

The wind tunnel used for our experiment is of the Effel type with an exit of 1.05m times 1.05m. The wind speed is adjustable between 2m/s and 20m/s.
An induction motor is employed as load in the experiment and the synchronized frequency is controlled by an inverter. For arbitrary determined frequencies, corresponding torque and rotational speed are measured by a torque converter and a revolution counter. From the results of the experiment the power coefficient Cp and the tip speed ratio are calculated to obtain the power characteristics for different blade types. Fig.7 shows the schematic of the experimental apparatus.
In the experiment of 202, 204, 302, 304, 402 and 404 blades, the wind speed in the wind tunnel is set at 4, 6, 8, 10 and 12m/s and the torque corresponding to the revolution is measured by gradually increasing the load.
The same procedure is followed for the blades of 5xx and 6xx, but they have the fixed blade numbers of three and five, respectively.

4. Results and consideration

4.1 Comparison among the blades with identical design tip speed ratio

As table2, If we look at the different number of blades with same tip speed ratio, say 3.4, we can see that the shorter the chord length, the larger the number of blades.
Torque coefficient of the tapered blades, power coefficient of the tapered blades, and the power coefficient of the inversely tapered blades at wind speed of 10m/s and the design tip speed ratio λ=3.4 are shown in the Fig.8,9 and 10, respectively to study the contribution of the blade numbers.

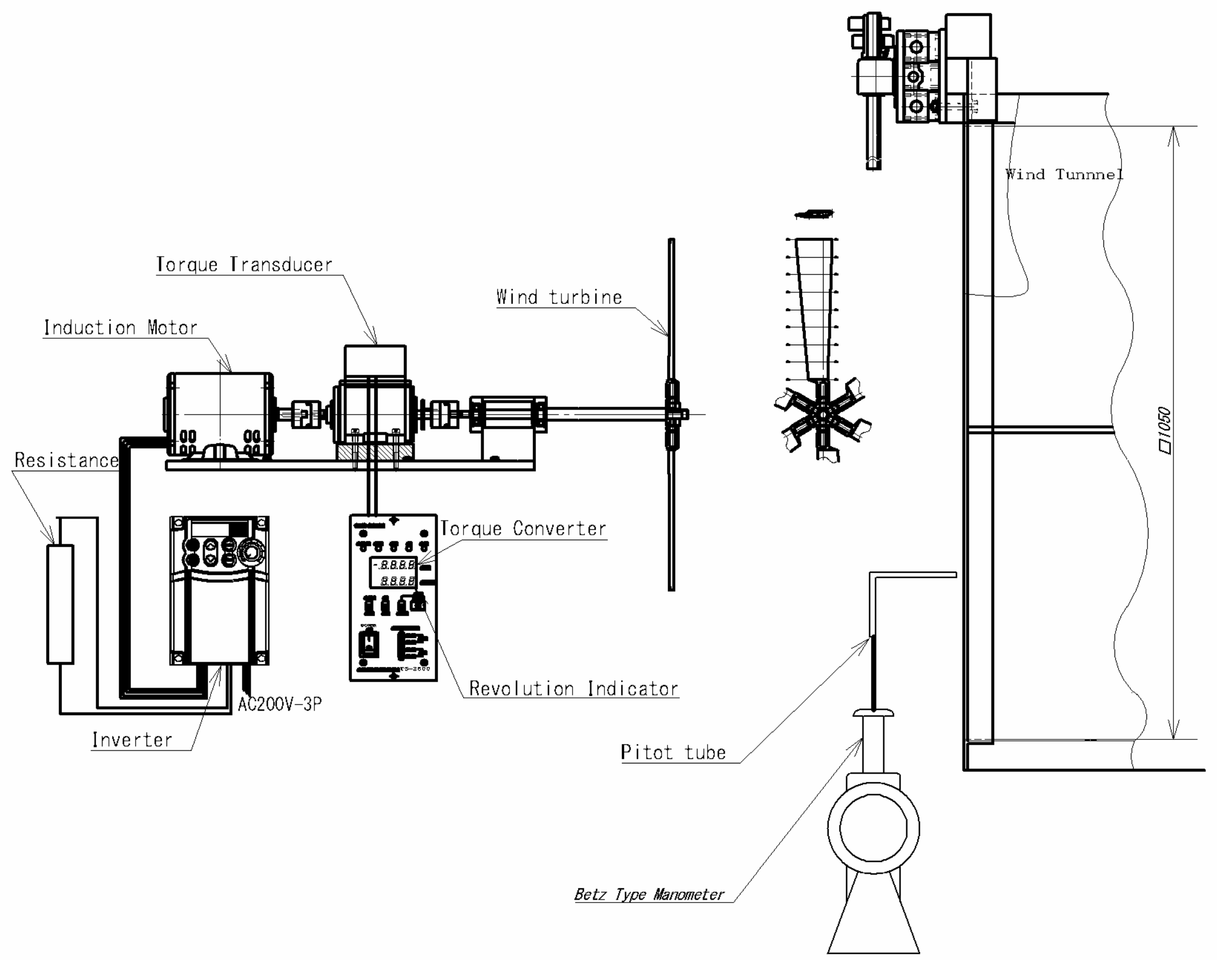


Fig. 7. Layout of the experimental apparatus

The results for the normally tapered blades show that the highest torque coefficient is obtained for the two bladed rotor and the maximum torque coefficient decreases with the increase of blade-number. However, tip speed ratio corresponding to each maximum torque coefficient increases with the number of blades.

The maximum power coefficients are over 0.38 for 2- to 5-bladed rotor while that for 6-bladed rotor is under 0.3. The highest power coeffient, Cpmax=0.39 is obtained for the 3-bladed rotor when λ=4.06.

However, six bladed rotor has lower values than other bladed type. Table 3 shows the calculated result of Reynolds number of these rotors at 80% position of span. The Reynolds number of the six bladed rotor was lower than the other rotors.

	Rev.[rpm]	Chord length	Radius[mm]	Tip speed[m/s]	Re. Number
2 bladed	1225	75.3	300	38.48451	1.9E+05
3 bladed	1293	50.5	300	40.620793	1.3E+05
4 bladed	1327	38	300	41.688935	1.0E+05
5 bladed	1411	30.3	300	44.327872	8.6E+04
6 bladed	1427	22.5	300	44.830527	6.5E+04

Table 3. Calculated result of Reynolds number (Tapered blades)

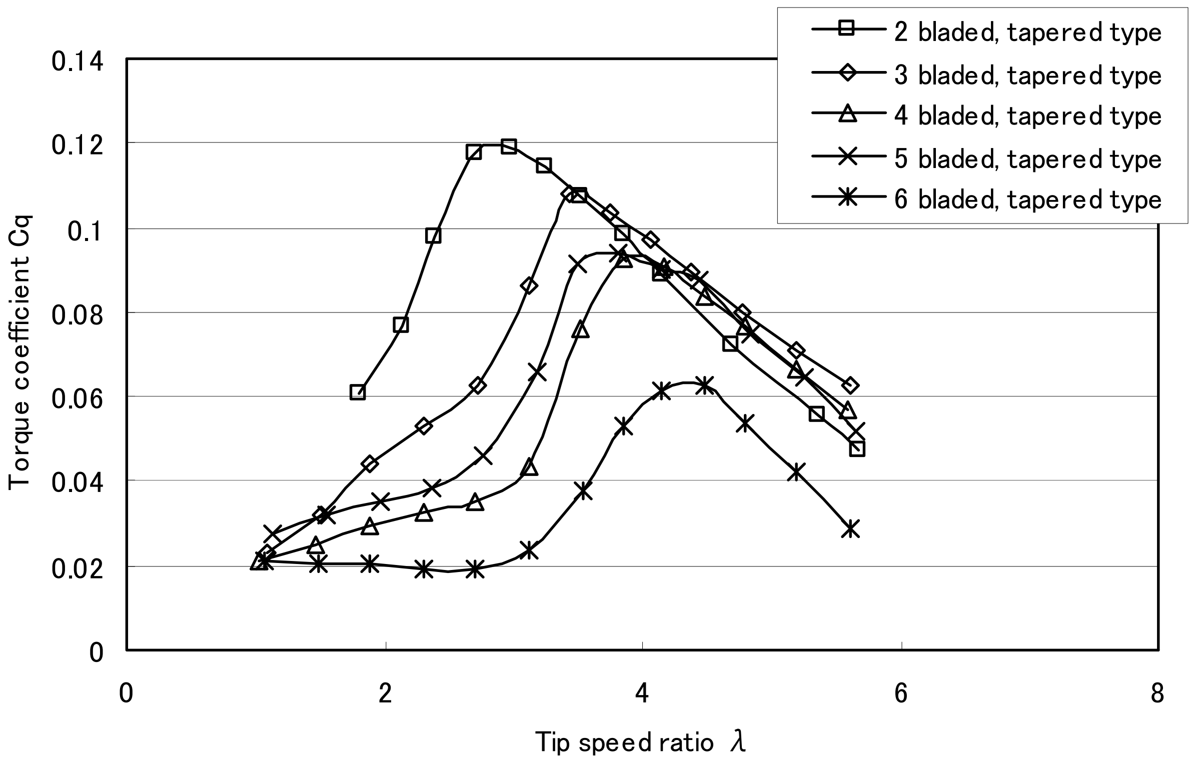


Fig. 8. Torque coefficient of taped types (λ =3.4)

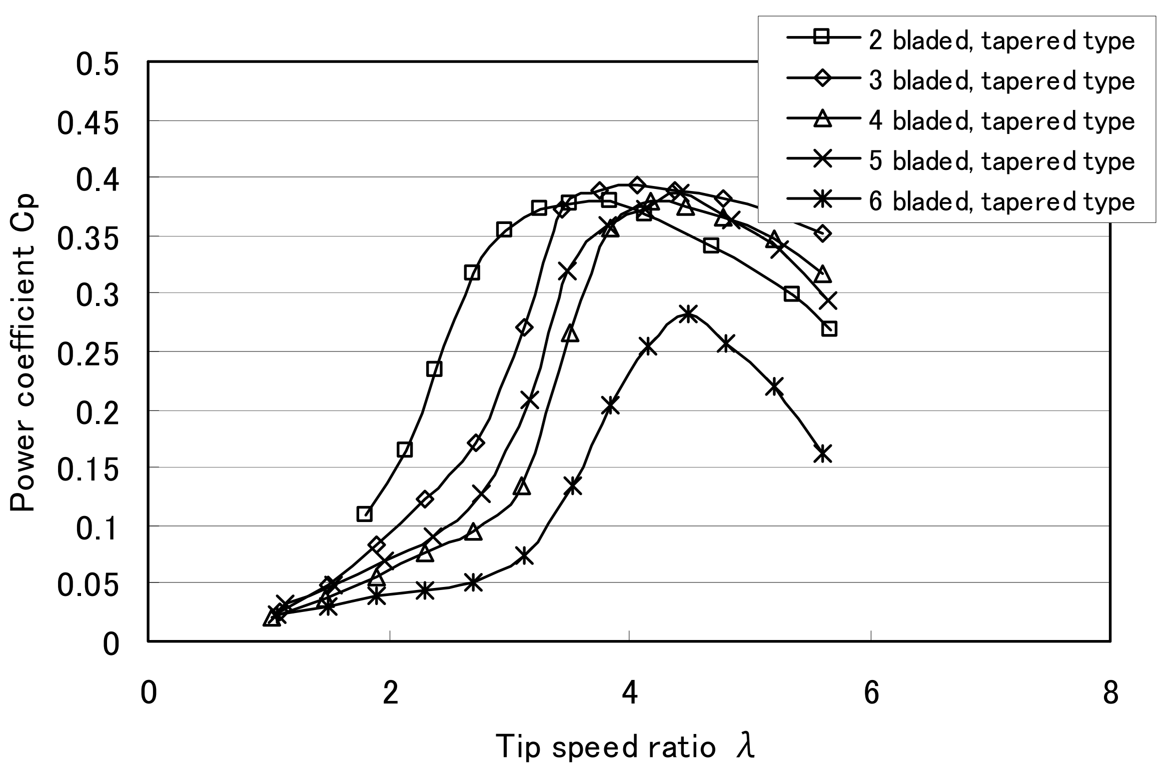


Fig. 9. Power coefficient of taped types (λ=3.4)

However, while Reynolds number of the five bladed rotor is as low as 8.6 times ten to the fourth power, power coefficient is not low. From these results, we found that the border of the superiority and inferiority of power coefficient of tapered type corresponds to the Reynolds number of 6.5 to 8.6 times ten to the fourth power.
For the inversely tapered blades, Cp for the two bladed rotor reached 0.38 when λ=3.72.
However, power coefficients of other rotors were lower than that of 2bladed rotor.
Table 4 shows the calculated result of Reynolds number of these rotors at 80% position of span. The impaired power coefficient of three bladed rotor the Reynolds number was two times ten to the fifth power.
From these results, We found that the border of the superiority and inferiority of power coefficient of inversely tapered type did not correspond to Reynolds number only.
As the result of performance comparison among the different blades with identical design tip speed ratio, we found that 3bladed tapered rotor was most efficient. Moreover, we found that power coefficient did not differ between tapered and inversely tapered rotor with the longest chord length.

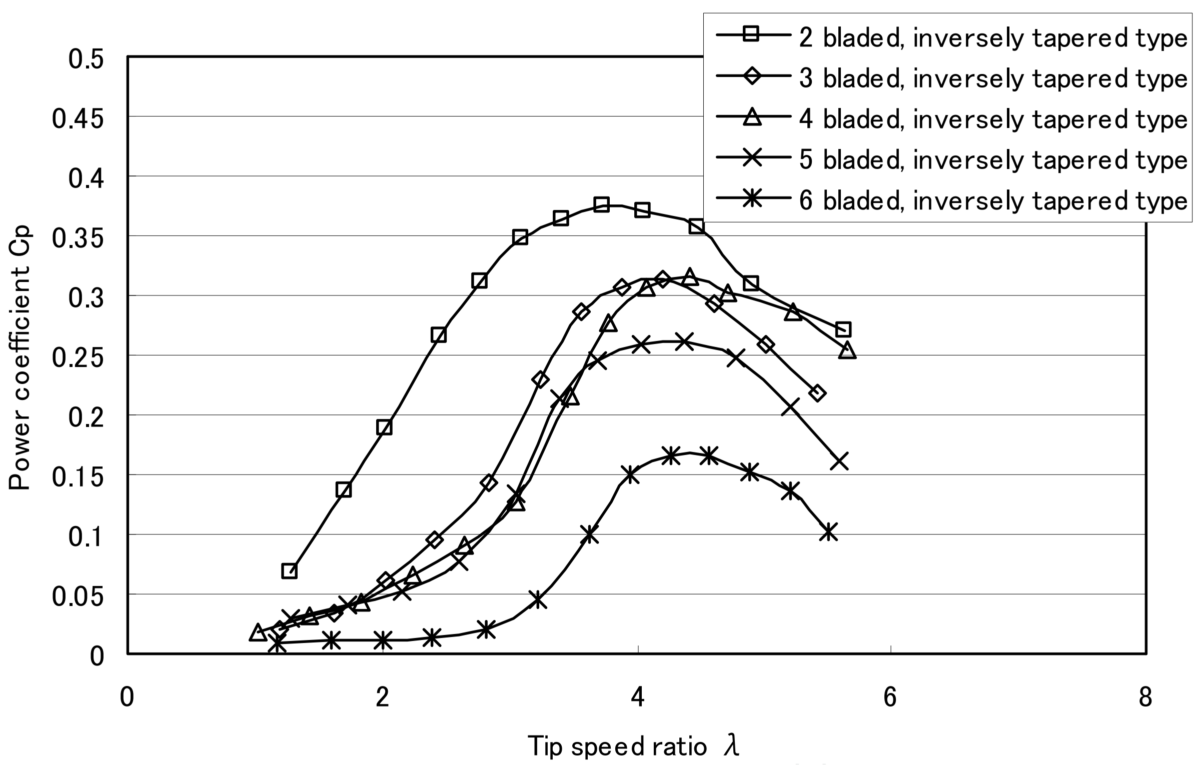


Fig. 10. Power coefficient of inversely taped types (λ=3.4)

	Rev.[rpm]	Chord length	Radius[mm]	Tip speed[m/s]	Re.Number
2 bladed	1186	102.5	300	37.259289	2.4E+05
3 bladed	1336	74.5	300	41.971678	2.0E+05
4 bladed	1407	55.2	300	44.202209	1.6E+05
5 bladed	1421	43.6	300	44.642032	1.2E+05
6 bladed	1452	33.6	300	45.615925	9.8E+04

Table 4. Calculated result of Reynolds number (Inversely tapered blades)

4.2 Characteristics of each blade in a rotor with different blade-number

The Fig.11 through 13 shows the characteristics of power coefficient for tapered blades, while the Fig.14 through 16 show those for inversely tapered blades.

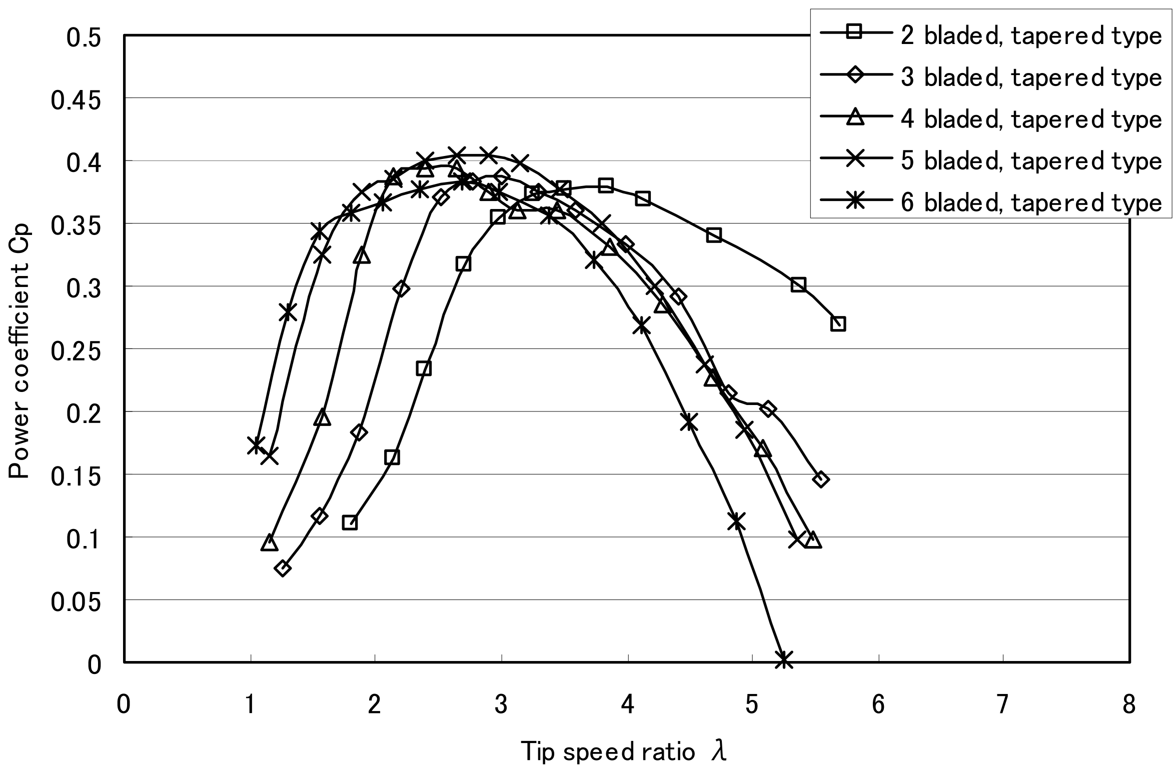


Fig. 11. Power coefficient of 202 (Tapered type)

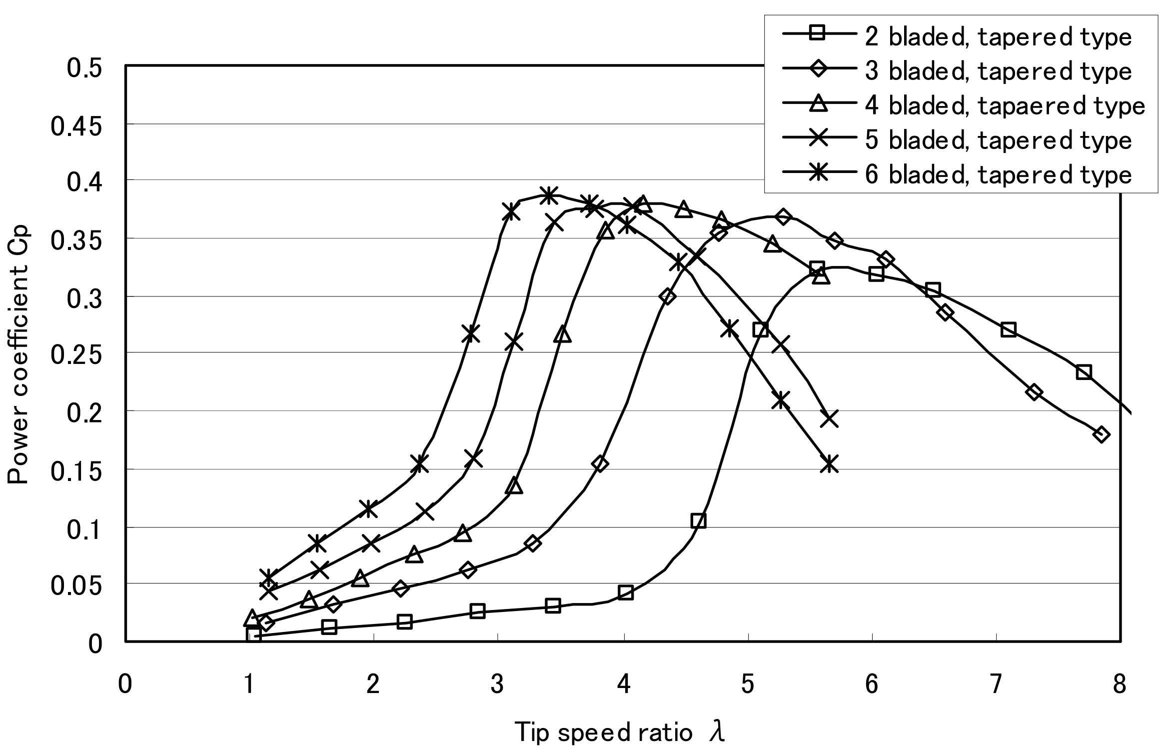


Fig. 12. Power coefficient of 302 (Tapered type)

For both tapered and inversely tapered types, the maximum power coefficient is obtained for the largest chord length. With regard to the number of the blades, five bladed rotor has highest maximum power coefficient.
In addition, the inversely tapered blades show an obvious increase of power coefficient with the number of blades than normally tapered blades.

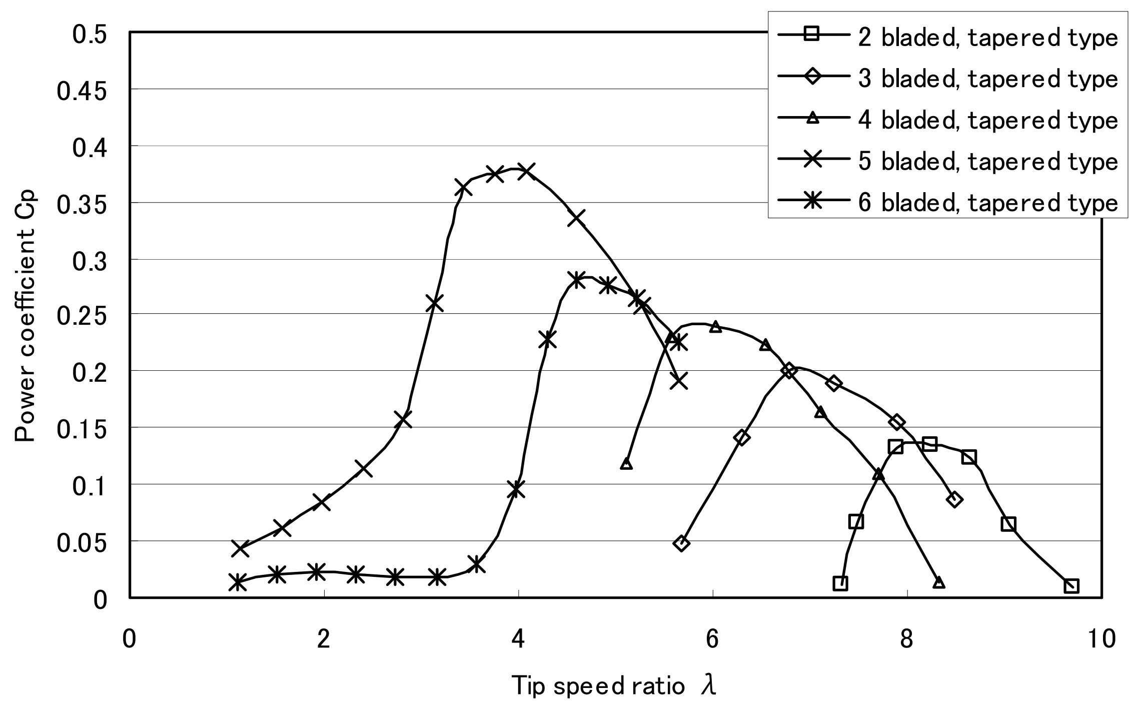


Fig. 13. Power coefficient of 402（Tapered type）

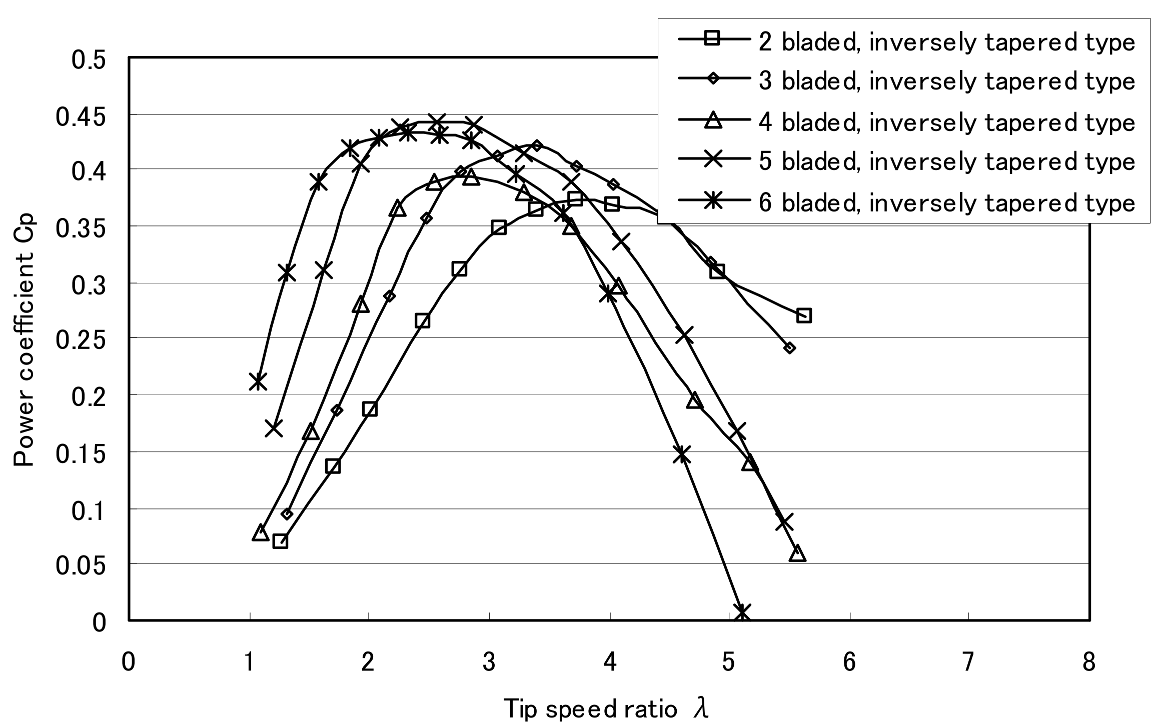


Fig. 14. Power coefficient of 204（Inversely tapered type）

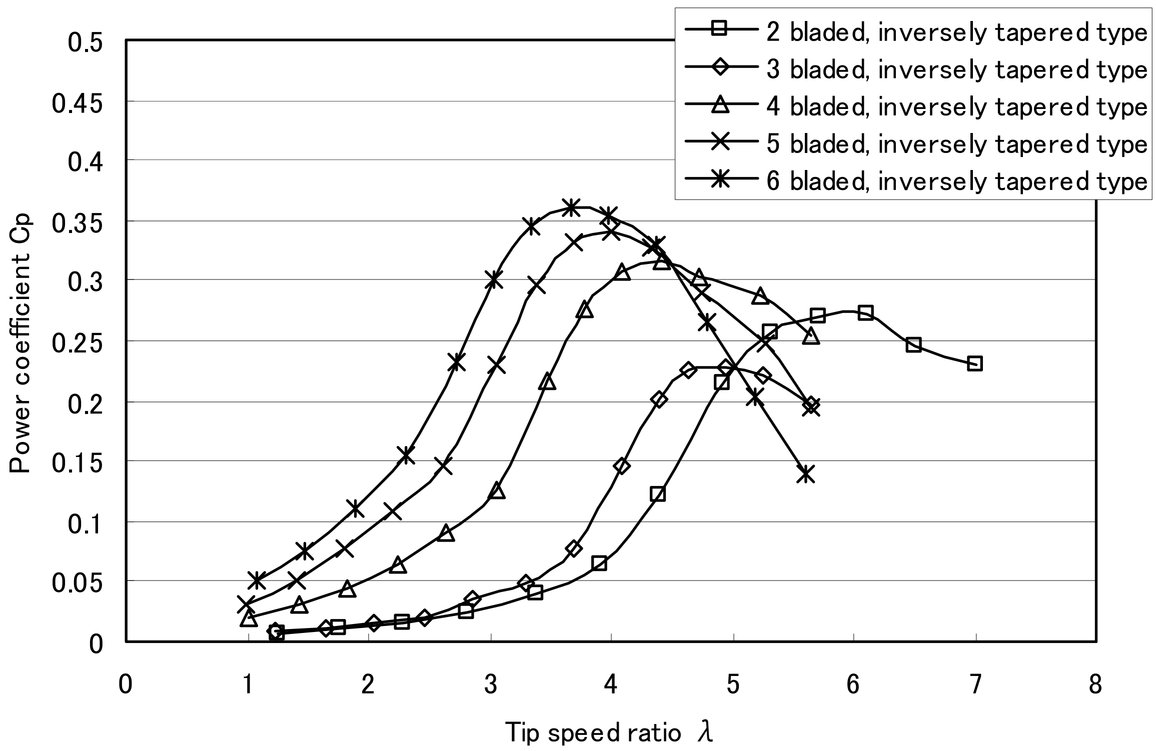


Fig. 15. Power coefficient of 304（Inversely tapered type）

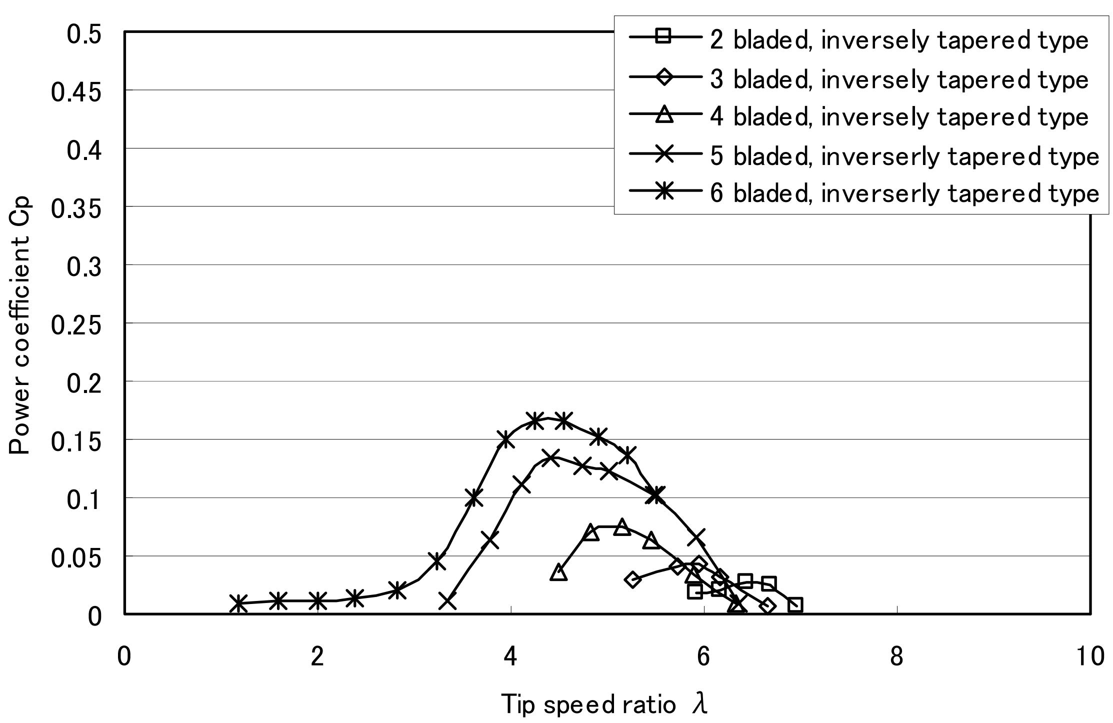
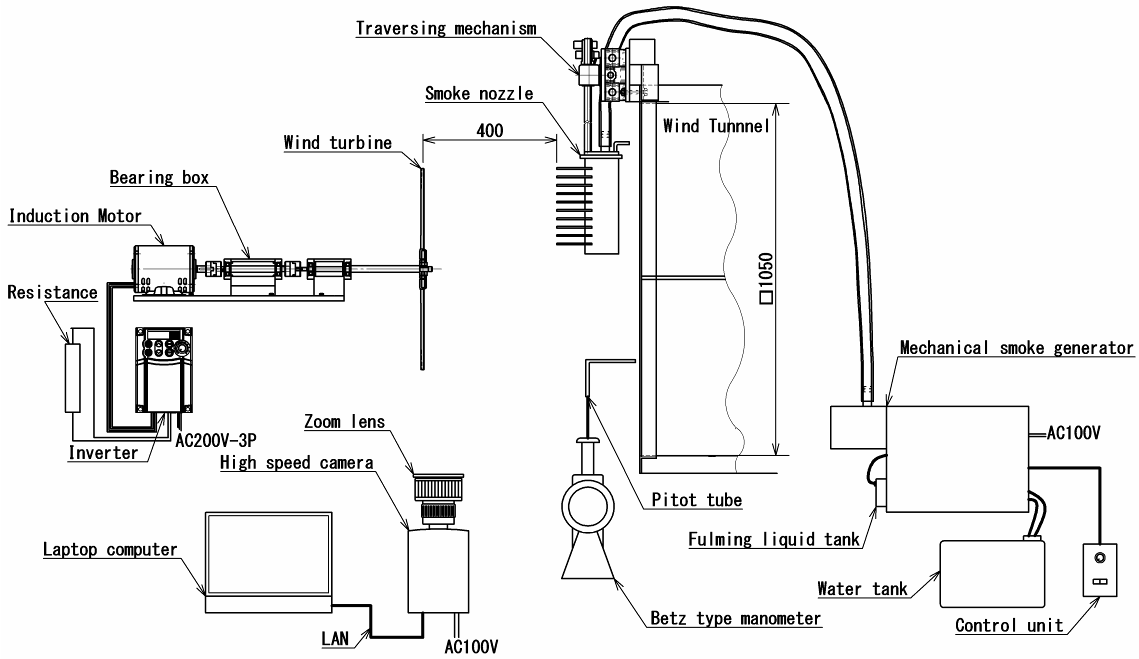


Fig. 16. Power coefficient of 404（Inversely tapered type）

From these results, we found that the performance of a rotor designed at low tip speed ratio (about λ=2) can be improved by increasing the number of blades and by adopting the inversely tapered blades.

5. Visualization around rotors

Our study is obvious that the power coefficient of inversely tapered type was higher than tapered type.
Then, the visualization tests were conducted and the behavior of the air flow were analyzed.



*Luminous source: Halogen lamp

Fig. 17. Visualization for experimental apparatus

5.1 Experiments

Figure 17 shows the experimental apparatus.
In this experiment, visualization test of the air flow around the rotor was conduced using the smoke of oil, high-speed camera and PIV analysis.
The authors took photos at the rotational speed correspond to the maximum power coefficient for the wind speed of 6, 8, and 10[m/s].
Figure 18 shows the grid of PIV analysis.

5.2 Results and consideration

The figure 19 and 20 shows the characteristics of Visualization for tapered blades, while the figure 21 and 22 show those for inversely tapered blades at 10m/s.
From the visualization test, the wind speed of the wake for tapered type is 5~8[m/s], on the contrary, the inversely tapered type is 3~6[m/s].
These results are presumed to be the latter type is effectively converting the air flow than the former type.

6. Conclusion

As the result of performance comparison among the blades with different design tip speed ratio, number of blades, and taper types, we obtained following conclusions.

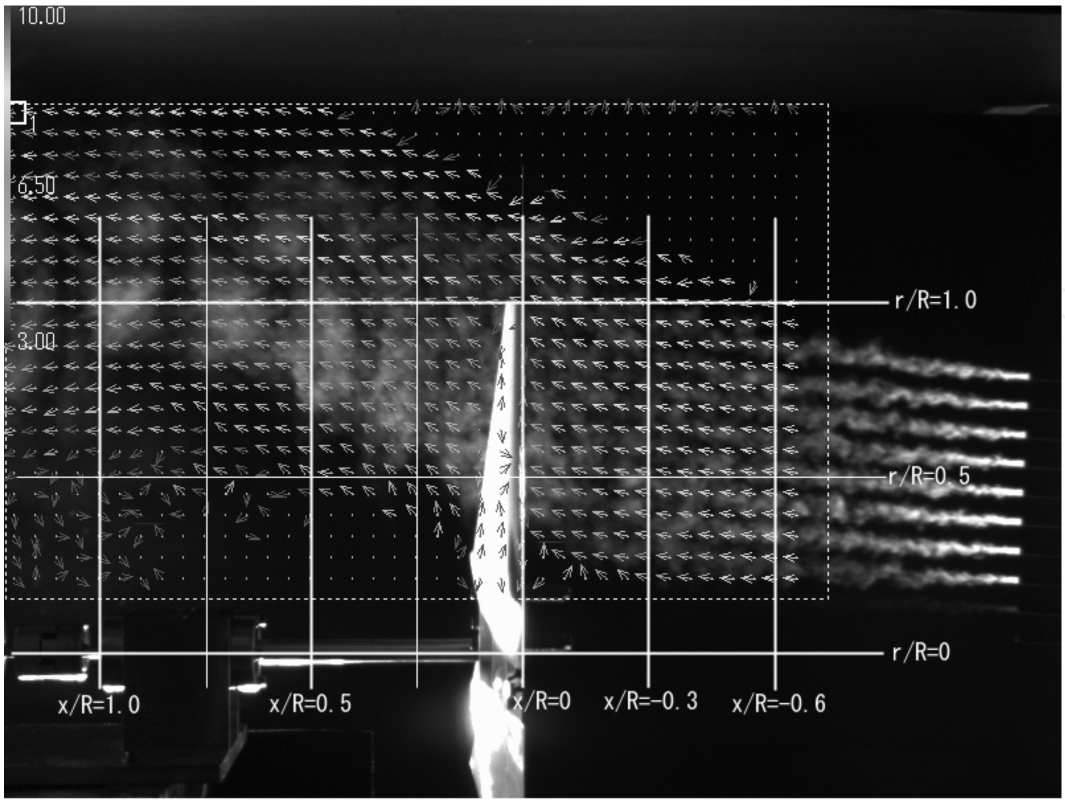


Fig. 18. Grid of PIV analysis

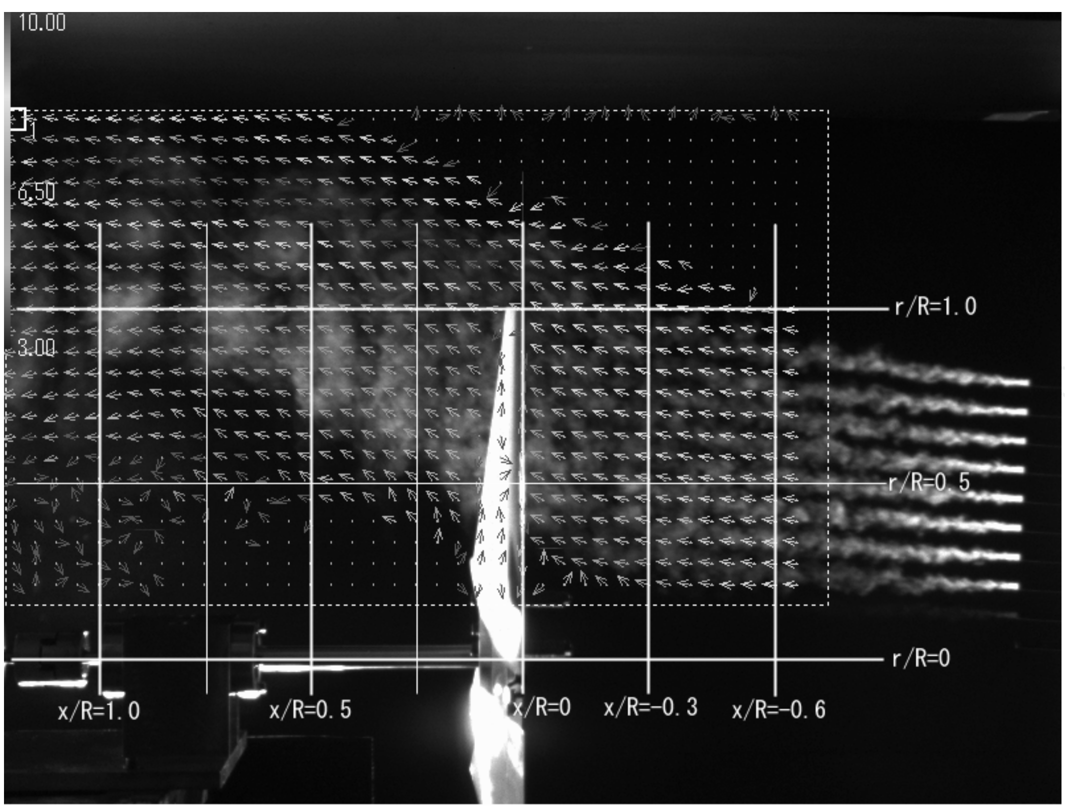


Fig. 19. Visualization analysis of vector line around tapered type rotor

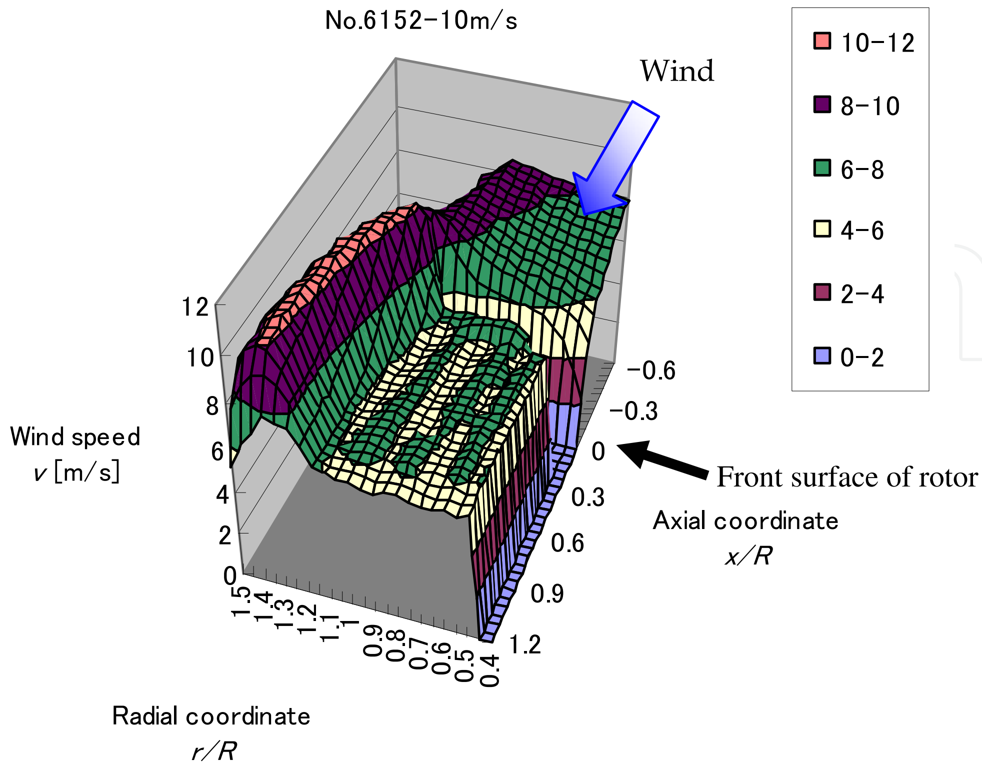


Fig. 20. Wind speed distribution around tapered type rotor

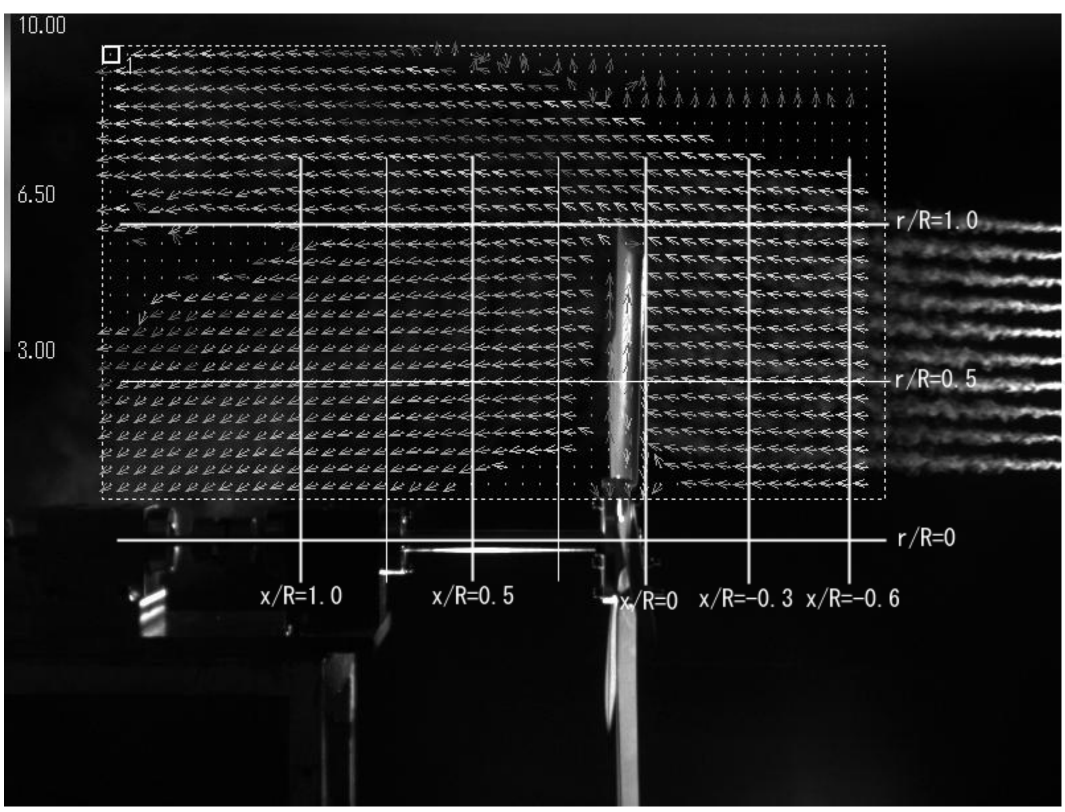


Fig. 21. Visualization analysis of vector line around inversely tapered type rotor

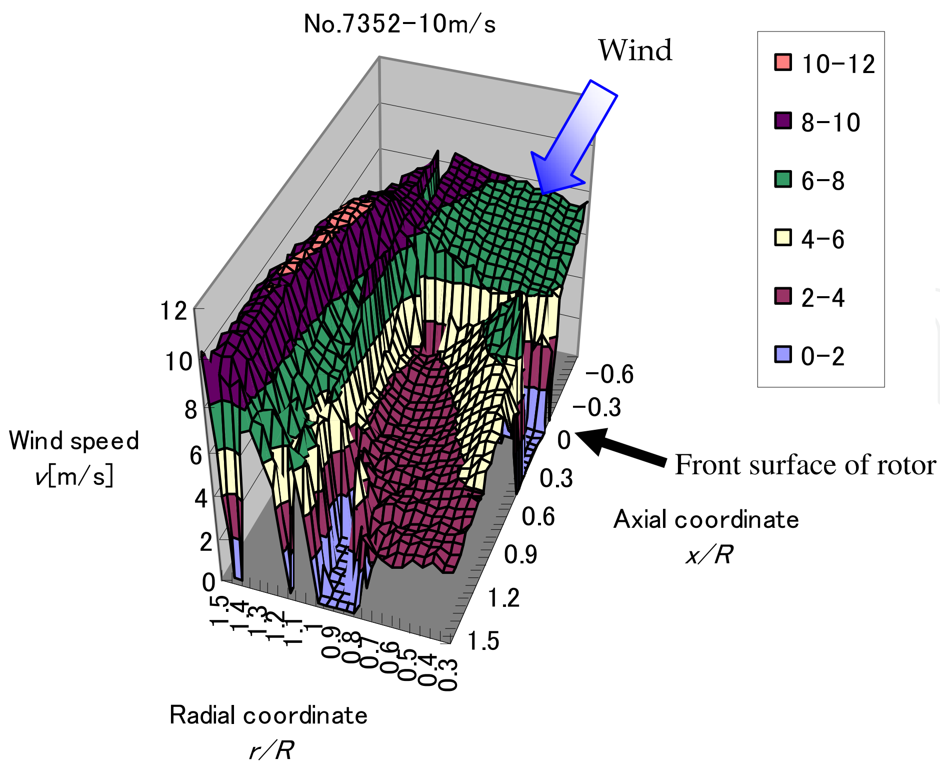


Fig. 22. Visualization analysis of vector line around inversely tapered type rotor

1. The border of the superiority and inferiority of power coefficient of tapered type corresponds to the Reynolds number of 6.5 to 8.6×10^4.
2. The border of the superiority and inferiority of power coefficient of inversely tapered type did not correspond to the Reynolds number only.
3. As the result of performance comparison among the blades with identical design tip speed ratio, we found that 3bladed tapered rotor was most efficient. In addition, the power coefficient did not differ between tapered and inversely tapered rotor for the longest chord length.
4. As the result of performance comparison between the blades with the longest chord length in a rotor with different blade-number, we found that 5 bladed tapered and inversely tapered rotor was most efficient. Moreover, power coefficient of inversely tapered rotor is larger than tapered type.

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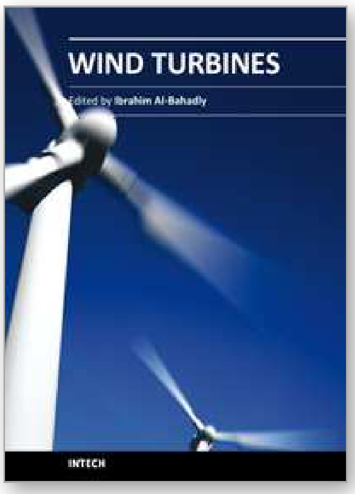

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