VERTICAL AXIS WIND TURBINE DESIGNED AERODYNAMICALLY AT TOKAI UNIVERSITY*

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About one year before the world-wide energy crisis of 1973, Dr. Shigeyoshi Matsumae, President of Tokai University, emphasized that research on the conversion of continuous energy resources was the most important problem in Japan, a country where oil or other resources are extremely limited.

We started to study wind energy conversion and developed research.

Recently we made a vertical axis wind turbine with a straight wing and an asymmetrical airfoil in its cross section, to keep a suitable pitching moment for high efficiency.

The vertical axis wind turbine has several advantages over the conventional propeller type horizontal axis wind turbine:

1) Omni-directional and able to convert wind energy from any direction.

2) The generator can be placed at ground level without any costly bevel gearing and will thereby allow simpler tower without the wind shear acting on the blades.

3) Turbine is free from the gyroscopic loading accompanied by wind direction tracking.

Concerning this vertical axis wind turbine, it is well known that J. M. Darrieus proposed that the turbine have a rotating shaft transverse to the flow of the current in 1925.

This is the so-called Darrieus wind turbine. At the Sandia Laboratories in the U. S., B. F. Blackwell made a 17-meter diameter Darrieus turbine. The rotor consists of three (or two) symmetric NACA0012 blades. Each blade is a symmetric airfoil in cross section and is shaped like a perfectly flexible cable of uniform density and cross section if spun around a vertical axis.

This blade shape has been designed by Troposkin. Therefore the rotation will not cause the blade to bend and thus the stress remains pure tension.

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On the other hand, we made a straight wing vertical axis wind turbine consisting of three blades. Each blade is an asymmetric airfoil in cross section (T. W. T. 11215-1) and supported by two arms of its cross section in symmetry (NACA0012).

The asymmetric airfoil blades in cross section are designed to keep a pitching moment under the rotation which is designed aerodynamically.

We emphasize that our wind turbine is particularly advantageous.

1) The elimination of variable pitch mechanism makes simple both its manufacturing and maintenance.

2) As the characteristics of the turbine are functionally distinct, various methods of aerodynamic controls can be easily introduced.

3) The span-wise bending moment of the blade due to centrifugal load cannot be eliminated in straight wing turbines, however, the conversion efficiency is higher than in the Darrieus turbine by about 5 per cent. It is more convenient to adopt straight wing configuration for a large turbine.

Now we want to show that the asymmetric airfoil in cross section (T. W. T. 11215-1) is more efficient than the symmetric airfoil (NACA0012) for the vertical axis wind turbine.

Figure 1 is a general view of the propotype of our wind turbine. Diameter is 2.5 m and blade span is 2.0 m.

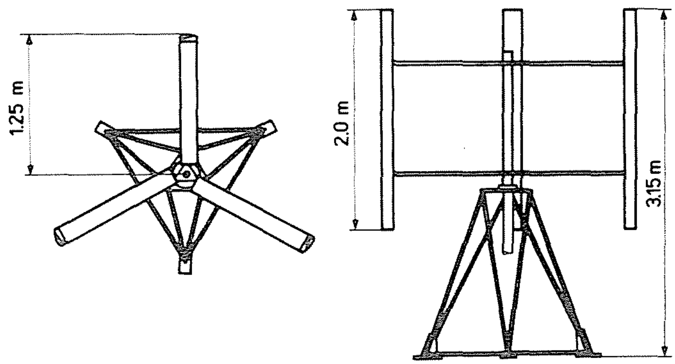

Fig. 1

The efficiency is defined in the following equation:

$$C_p = \frac{\text{output power}}{\frac{1}{2}\rho V_\infty^3 \times \text{cross section of wind turbine}},$$

where $\frac{1}{2}\rho V_\infty^3$ is the kinetic energy of the wind and ρ is the density of air.

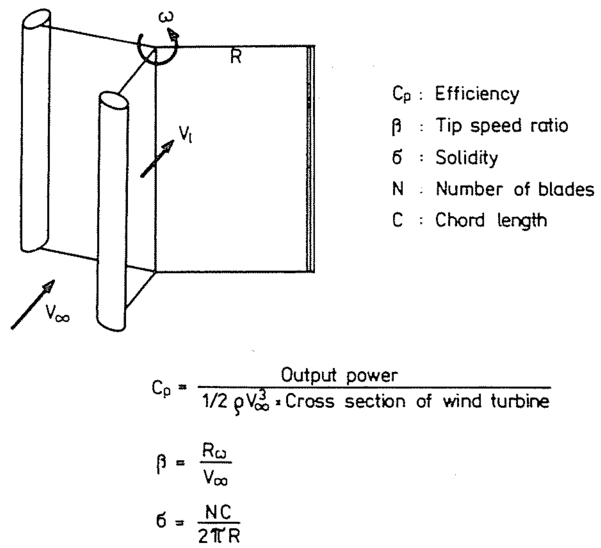

Fig. 2

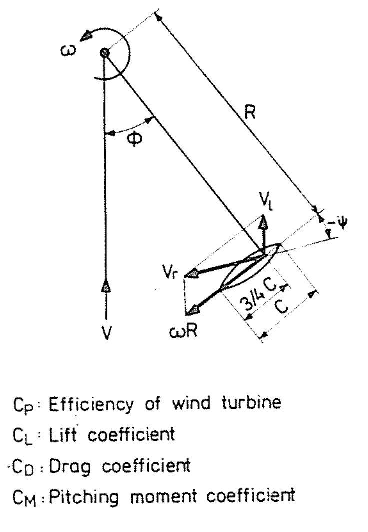

Fig. 3

If we take coordinates as shown in Fig. 3, the efficiency of the turbine is expressed in a following equation according to a theory of simple tube of flow.

$$C_{pl} = \frac{\sigma}{2} \int_0^{2\pi} \beta(1 - 2\beta \sin \Phi + \beta^2) \times (C_L \sin \psi - C_D \cos \psi - C_M l)\, d\Phi\,, \quad (1)$$

where

$$\psi = \tan^{-1}\left(\frac{\cos \Phi}{\sin \Phi - \beta}\right), \qquad (\sin \Phi - \beta < 0),$$

$$\psi = \tan^{-1}\left(\frac{\cos \Phi}{\sin \Phi - \beta}\right) + \pi, \qquad (\sin \Phi - \beta > 0). \tag{2}$$

In this equation l in the term of pitching moment is $l = \frac{C}{R}$.

In the equation (1), β is used as the local velocity V_l, where $V_l = V_\infty(1-a)$, and a is a factor of velocity decrease.

Then,

$$C_p = C_{pl}(1-a)^3,$$

and except in the case of small β the value of a is expressed

$$a = \frac{1}{1 + (1/K\sigma\beta)},$$

where K is nearly 2.4.

Then finally the efficiency is expressed in the following equation:

$$C_p = \frac{\sigma\beta/2}{(1+K\sigma\beta)^3} \int_0^{2\pi} (1 - 2\beta \sin \Phi + \beta^2) \times (C_L \sin \psi - C_D \cos \psi - C_M l) \mathrm{d}\Phi. \tag{3}$$

On the other hand, from equation (2),

$$\frac{\mathrm{d}\Phi}{\mathrm{d}\psi} = \frac{1 - 2\beta \sin \Phi + \beta^2}{\beta \sin \Phi - 1}.$$

Then from the equation (3),

$$C_p = \frac{\sigma\beta/2}{(1+K\sigma\beta)^3} \int_\alpha \frac{(1 - 2\beta \sin \Phi + \beta^2)^2}{|\beta \sin \Phi - 1|} \times (C_L \sin \psi - C_D \cos \psi - C_M l)|\mathrm{d}\psi|.$$

As the arm is connected perpendicularly to the blades, the angle ψ, (flowing angle) is equal to angle α (attack angle).

Then introduce a weighting function,

$$W_L = \frac{(1-2\beta \sin \Phi + \beta^2)^2}{|\beta \sin \Phi - 1|} \sin \psi ,$$

$$W_D = \frac{(1-2\beta \sin \Phi + \beta^2)^2}{|\beta \sin \Phi - 1|} \cos \psi ,$$

$$W_M = \frac{(1-2\beta \sin \Phi + \beta^2)^2}{|\beta \sin \Phi - 1|} l .$$

Then,

$$C_p = \frac{\sigma\beta/2}{(1+K\sigma\beta)^3} \int_\alpha (W_L C_L + W_D C_D + W_M C_M)|\mathrm{d}\alpha| ,$$

and the torque coefficient is,

$$C_T = \frac{\sigma/2}{(1+K\sigma\beta)^2} \int_\alpha (W_L C_L + W_D C_D + W_M C_M)|\mathrm{d}\alpha| .$$

From these equations we can deduce the contribution of each term to the efficiency of the turbine.

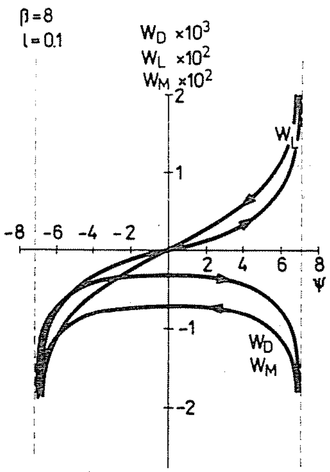

Fig. 4

Figure 4 shows the value of each weighting function in the case of $\beta=8$ and $l=0.1$ (ratio of chord lenght to radius of turbine). From this figure it is clear that the following conditions are necessary for high efficiency:

1) Gradient of lift for α must be large.
2) Coefficient of drag for α must be small.
3) Coefficient of drag must be symmetric about zero lift angle.
4) Coefficient of pitching moment must be large.

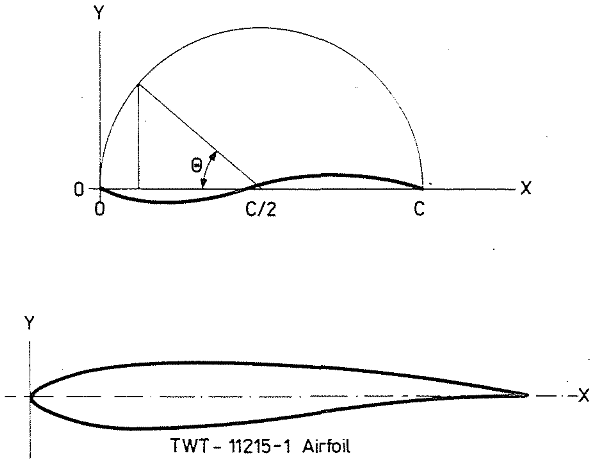

Fig. 5

In order to satisfy the above characteristics, we designed the new airfoil whose camber line is reversed at a suitable point. (Fig. 5)

Figure 6 and Fig. 7 show the result of experimental studies of the characteristics of airfoil (NACA0012) and the newly designed airfoil (T. W. T. 11215-1).

As the figures show, airfoil NACA0012 is preferable so long as lift-and drag coefficient are concerned. That is, drag coefficient is symmetric about zero lift angle. However, the pitching moment coefficient is not always negative and large in the angle of attack ranging up to plus-minus 10 degree.

Airfoil T. W. T. 11215-1 has a large negative pitching moment and the drag coefficient is symmetric about zero lift angle. Gradient of coefficient of lift is also large within the attack angle α is about $\pm 11^\circ$ (actually the attack angle changes from about $+11^\circ$ to -11° for one revolution).

Figure 8 shows the curve of C_p for the value of β and it is very clear that efficiency becomes high when the airfoil has a pitching moment.

Finally the Fig. 9 shows the characteristic curve of the proto-type of T. W. T. and the detailed characteristics are in the next specifications.

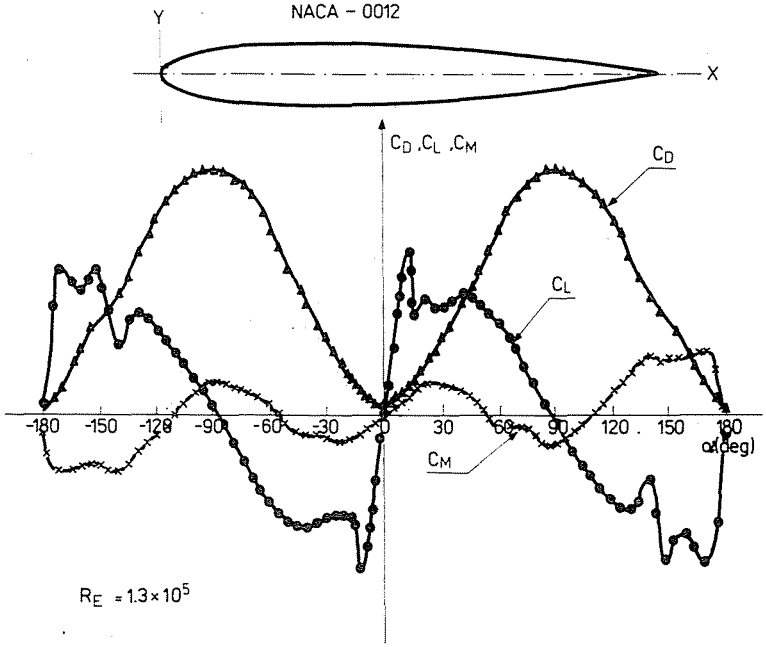
Y
NACA - 0012
X
C_D, C_L, C_M
C_D
C_L
C_M
-180 -150 -120 -90 -60 -30 0 30 60 90 120 150 180
α(deg)
$R_E = 1.3 \times 10^5$

Fig. 6

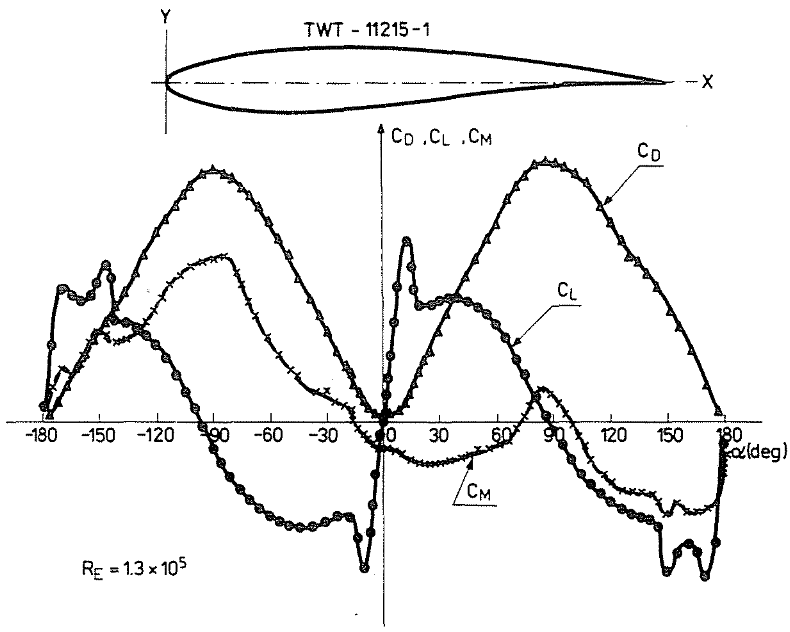
Y
TWT - 11215-1
X
C_D, C_L, C_M
C_D
C_L
C_M
-180 -150 -120 -90 -60 -30 0 30 60 90 120 150 180
α(deg)
$R_E = 1.3 \times 10^5$

Fig. 7

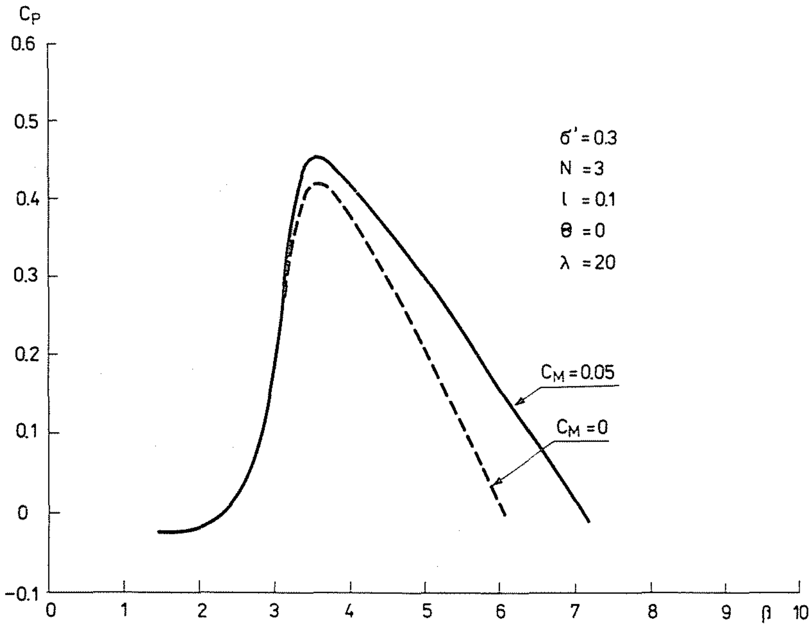
Cp
0.6
0.5
0.4
0.3
0.2
0.1
0
−0.1
0
1
2
3
4
5
6
7
8
9
β
10
σ' = 0.3
N = 3
l = 0.1
θ = 0
λ = 20
CM = 0.05
CM = 0

Fig. 8

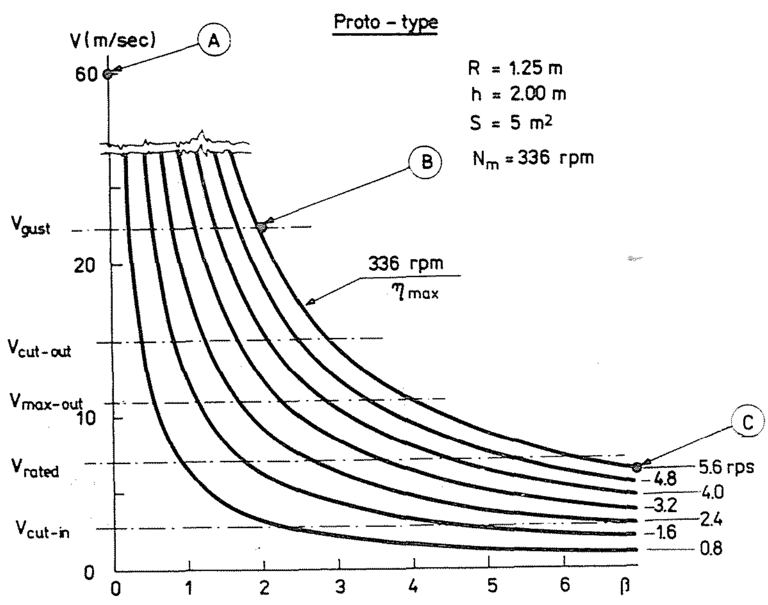
Proto – type
V (m/sec)
A
60
R = 1.25 m
h = 2.00 m
S = 5 m2
Nm = 336 rpm
B
Vgust
20
336 rpm
ηmax
Vcut-out
Vmax-out
10
C
Vrated
5.6 rps
4.8
4.0
3.2
2.4
1.6
0.8
Vcut-in
0
0
1
2
3
4
5
6
β

Fig. 9

Performance:

(Following data are at 10 m/sec wind velocity)

Turbine shaft output	1.5 Kw
Rotational speed of turbine	260 RPM
Generator output	1.0 Kw
Rotational speed of generator	364 RPM

Design wind velocities:

Cut-in velocity	3.8 m/sec
Rated velocity	10 m/sec
Maximum output velocity	12 m/sec
Cut-out velocity	15 m/sec
Gust velocity	22.5 m/sec
Ultimate velocity	60 m/sec

Specifications of five square meter wind turbine generator

Wind turbine:

Diameter	2.5 m
Blade span	2.0 m
Airfoil of blades	TWT 11215-1-4012
Airfoil of arms	NACA0012
Controls	Aerodynamic control (Spoilers on arms)
Starter	None
Gear ratio of transmission	1:1.4
Generator Zephyr VLS-PM 311B	
Rated output	1.5 Kw at 450 RPM
Rated voltage	24 V or 48 V

Summary

Tokai University has recently completed an investigation on a vertical axis wind turbine to utilize wind energy, one of the inexhaustible energy sources.

The vertical axis wind turbine has several advantages over the conventional propeller-type wind turbine.

1) Omni-directional and able to convert wind energy from any direction.

2) The generator can be placed at ground level without any costly bevel gearing and will thereby allow simpler tower without the wind-shear acting on the blades.

3) Turbine is free from the gyroscopic loading accompanied by wind direction tracking.

The paper emphasizes the straight-wing type vertical axis wind turbine which is particularly advantageous.

1) The elimination of variable pitch mechanism makes simple both its manufacturing and maintenance.

2) As the characteristics of the turbine are functionally distinct, various methods of aerodynamic controls can be easily introduced.

3) The span-wise bending moment of the blade due to centrifugal load cannot be eliminated in straight wing turbines, however the conversion efficiency is higher than in Darrieus turbines by about 5 per cent. It is more convenient to adopt straight-wing configuration for a large turbine.

This paper emphasizes also the characteristics of the blade. Each blade has an asymmetric airfoil in cross section, especially designed to extract wind energy as efficiently as possible.

Various fields of application of wind turbines are discussed also in this paper.

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