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Effects of Wing Section on Mean Characteristics and Temporal Torque Variation for a Small Straight-Bladed Vertical Axis Wind Turbine*

Seiji YAMADA**, Tomohiro TAMURA** and Shinsuke MOCHIZUKI***
** Yamaguchi Prefectural Industrial Technology Institute, 4-1-1 Asutopia,
Ube City, Yamaguchi, 755-0195, Japan
E-mail: seiji@iti-yamaguchi.or.jp
*** Development of Mechanical Engineering, Yamaguchi University, 2-16-1 Tokiwadai,
Ube City, Yamaguchi, 755-8611, Japan

Abstract
The net rotor torque generated by a straight-bladed vertical axis wind turbine has temporal variation for an azimuth angle of the blade. The torque variation should be investigated to understand the performances of the wind turbine. The blade camber and thickness are important to determine the characteristics of the wind turbine. We have studied effects of the blade camber and thickness on the mean characteristics and temporal torque variation at any azimuth angle of the blade. The mean torque and power increase with the smaller camber and the larger blade thickness over relatively lower tip speed ratio. The maximum mean torque and power coefficient take the largest value at certain blade thickness. The maximum value of the torque variation emerges at an azimuth angle of the blade located in upstream, and it has significant contribution to the mean torque. In particular, over relatively lower tip speed ratio, the maximum value of the torque variation remarkably increases with the smaller camber and the larger blade thickness.

Key words: Straight Bladed Vertical Axis Wind Turbine, Torque Variation, Mean Characteristics, Wing Section, Camber, Blade Thickness

1. Introduction

The present experimental study focuses on a small wind turbine which has possibility of utilization of the renewable energy. A straight-bladed vertical axis wind turbine (This is called commonly Straight Darrieus Turbine) is one of the promising wind turbines, since it is free from the directional control for wind(1) and has simple blade structure. However the net rotor torque of the wind turbine is supposed to be varied with an azimuth angle of the blade(2), because relative velocity and angle of the attack for relative velocity are temporally varied. This temporal torque variation may influence the mean characteristics of the wind turbine, the response for change of the wind direction, and the vibration of the prop. Therefore, the torque variation should be investigated to understand the performances of the wind turbine.

The wing section, the wing tip shape, and solidity etc. certainly affect on the performances of the wind turbine. So far studies of effects of solidity and wing section on the wind turbine(3-5), research and development of high-performance airfoil(6) etc. were made in terms of mean characteristics. There were also some attempts to measure the torque variation in the azimuth angle(7-9). However studies of effects of the wing section on the mean characteristics associated with the temporal torque variation have been hardly seen. Effects of the camber and the blade thickness in the wing section on the mean torque and power characteristics associated with the torque variation at any azimuth angle of the blade for the small wind turbine are examined in the present experimental study.

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2. Dynamics of wind turbine

The dynamic model of the wind turbine is shown in Fig. 1. The dynamic equation of the wind turbine is

$$I_{wt}\frac{d\omega}{dt}=T_w-T_a, \tag{1}$$

where T_w is the net torque [N·m], T_a is the torque generated from the wind turbine(i.e. measured torque)[N·m], ω is the angular velocity of the rotor[rad/sec], and I_{wt} is the inertial moment of the wind turbine [kg·m^2]. The net torque of the rotor by the wind is calculated by

$$T_w=T_a+I_{wt}\frac{d\omega}{dt}. \tag{2}$$

The wind turbine was connected to the motor via the torque converter, and the torque of the rotor is measured under constant rotational speed. If the inertial term is ideally neglected, namely $T_w=T_a$. However, actually ω has certain variation due to fluctuation in T_w [10]. In the present experiment the inertial term is remained in order to calculate the net torque variation in a rotation. On the mechanical friction effect in measured torque, the friction torque, which is measured at each rotational speed without the wind turbine, is added the measured torque.

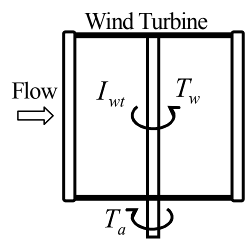


Fig. 1 Dynamic model of the wind turbine

3. Experimental Techniques

The experimental apparatus and coordinate system are shown in Fig. 2. U_0 is wind velocity[m/s], θ is the azimuth angle of reference blade[deg]. The wind turbine was located in front of the wind tunnel test section with a 1000mmW×1000mmH rectangular cross section. The distance of between the wind tunnel nozzle exit and the center of rotation of the wind turbine is 450mm. The wind turbine was located within the potential core of the flow produced by the wind tunnel. The velocity of the flow approaching the wind turbine was measured by a pitot tube at just exit of the wind tunnel. The wind turbine was connected to the motor via the torque converter and controlled in a constant rotational speed by the inverter. The torque of the rotor, the rotational speed, and the azimuth angle of the reference blade were

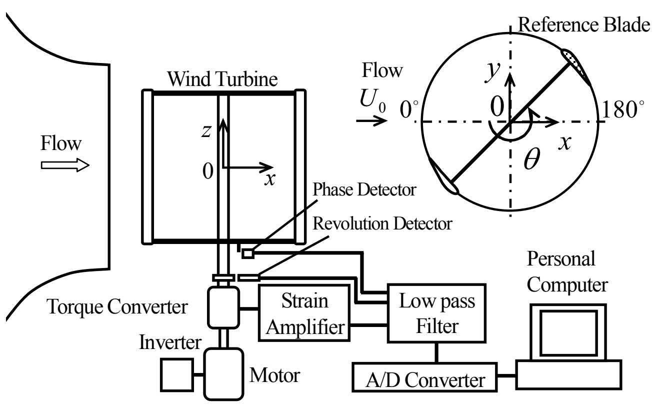


Fig. 2 Apparatus and coordinate system

measured simultaneously, and the time series data were stored for analysis. The mean torque, the mean rotational speed, phase averaged measured torque, phase averaged angular velocity, and phase averaged angular acceleration were calculated from analysis of the data. The net phase averaged torque by the wind was calculated using phase averaged measured torque and phase averaged angular acceleration by Eq. (2). Conventional time mean and phase average of arbitrary function $F(t)$ are defined as

$$\bar{F}(t) = \lim_{\Delta T \to \infty} \frac{1}{\Delta T} \int_0^{\Delta T} F(t)dt \,, \tag{3}$$

$$\langle F(t) \rangle_T = \lim_{N \to \infty} \frac{1}{N} \sum_{k=0}^{N-1} F(t + kT) \,, \quad (0 \le t \le T \,,\ T \text{ :a period}) \,. \tag{4}$$

The net time mean torque, time mean power, and the net phase averaged torque coefficient are defined by

$$C_T = \frac{\bar{T}_w}{1/2\rho U_0^{\,2} Ar} \,, \quad C_P = \frac{\bar{T}_w \bar{\omega}}{1/2\rho U_0^{\,3} A} \,, \quad \langle C_T \rangle_T = \frac{\langle T_w \rangle_T}{1/2\rho U_0^{\,2} Ar} \,, \qquad (5), (6), (7)$$

where ρ is density of air [kg/m^3], A is projected area [m^2], and r is rotor radius [m].

The wind turbine has rotor radius of $r = 0.3$m, blade span of $b = 0.6$m, chord length of c=150mm, number of blades of N=2 or 1(solidity $\sigma = Nc/2\pi r$ =0.16 at N=2). r is defined as distance between 0.3c wing chord position on the mean line and the center of rotation of the wind turbine. The wings were mounted on the hub at the angle where the output power is the maximum for each wing shape. The wing section of the blade was designed according to NACA 4 digit wing section, because this is typical wing section and wing section parameters can be easily varied systematically. Details of the blades are listed in Table 1. All experiments were made at wind velocity U_0=6m/s. This study is focused on performance of practical small wind turbine at wind speed as low as 3m/s. Reynolds number $\mathrm{Re} = 2rU_0/\nu$ is 2.4×10^5 with r=600mm and U_0=3m/s. When r is 300mm, wind velocity U_0 is 6m/s. Another Reynolds number $\mathrm{Re}_c = Wc/\nu$ is 2.5×10^4～1.4×10^5 at the tip speed ratio of 1.41. Where W is relative velocity and ν is kinematic viscosity of air.

Table 1 List of Blades (f : camber, t : thickness)

Wing section	f/c [%]	t/c [%]
NACA0020	0.00	20
NACA3520	3.00	20
NACA6520	6.35	20
NACA8520	8.00	20
NACA6518	6.35	18
NACA6525	6.35	25
NACA6530	6.35	30

4. Experimental Results and Discussion

4.1. The time mean characteristics

4.1.1. Effects of camber

Figure 3 shows effects of camber on the time mean torque and power characteristics. Horizontal axis is the tip speed ratio λ $(= r\bar{\omega}/U_0)$, and vertical axis is the time mean torque coefficient C_T and the time mean power coefficient C_P. C_T increases with the smaller camber over relatively lower tip speed ratio of λ<1 in Fig. 3. The maximum of C_T, $(C_T)_{\max} \cong 0.17$, on NACA0020 and NACA3520 are largest for the camber variation. $(C_T)_{\max}$ decreases with the larger camber in a range of f/c>0.03. $(C_T)_{\max}$ of NACA8520 is significantly small. λ at $(C_T)_{\max}$ tends to decrease with the smaller camber, and λ is about

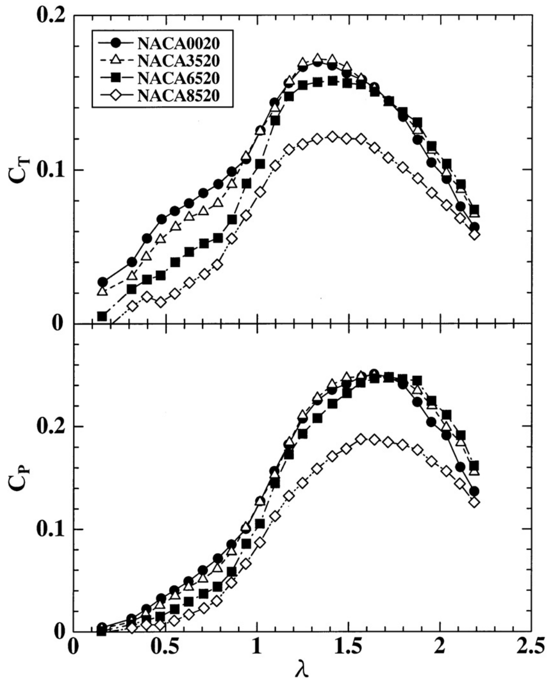


Fig. 3 Effects of camber on the time mean torque and power characteristics

1.33 on NACA0020 and NACA3520. Beyond the maximum C_T, the decreasing of C_T against λ is reduced with the larger camber.

The torque characteristics reflect to the mean power coefficient C_P. C_P increases with the smaller camber in a range of λ <1. $(C_P)_{\max}$ of NACA8520 is significantly smallest. $(C_P)_{\max}$ of the other wings are approximately 0.25. C_P takes the maximum in a range of λ =1.57-1.72 for all camber wings.

The above mentioned results suggest that the mean torque and power increase with the smaller camber over relatively lower tip speed ratio of λ <1. It is suggested that the rotational acceleration is better with smaller camber wings.

4.1.2. Effects of thickness

(1) Asymmetry wing section

Figure 4 shows effects of the thickness for asymmetry wing section on the mean torque and power characteristics. C_T increases with the larger blade thickness over relatively lower tip speed ratio of λ <1.1 in Fig.4. $(C_T)_{\max}$ of NACA6525 is largest for the thickness variation. Therefore, $(C_T)_{\max}$ takes the largest value at certain blade thickness. λ at $(C_T)_{\max}$ decreases with the larger blade thickness toward about 1.25 in a range of $t/c \geq 0.25$.

The torque characteristics reflect to C_P. C_P increases with the larger blade thickness over relatively lower tip speed ratio of λ <1.1. $(C_P)_{\max} \cong 0.25$ of NACA6520 and NACA6525 is largest for the thickness variation. Therefore, $(C_P)_{\max}$ takes the largest value at certain blade thickness. λ at $(C_P)_{\max}$ decreases with the larger blade thickness toward about 1.64 in a range of $t/c \geq 0.25$.

The above mentioned results suggest that the mean torque and power increase with the larger blade thickness over relatively lower tip speed ratio. However, $(C_T)_{\max}$ and $(C_P)_{\max}$ have the largest value at certain blade thickness.

(2) Symmetry wing section

Figure 5 shows effects of the thickness for symmetry wing section on the mean torque and power characteristics. C_T of the thinnest blade NACA0018 is smallest in a range of 0.6< λ <1.4, and C_T roughly increases with the larger blade thickness in a range of 0.6< λ <1.2. In detail, C_T of NACA0025 is largest in a range of 0.9< λ <1.4. C_T of the thickest blade NACA0030 is smallest in a range of λ <0.6. The tendency that C_T increases with the larger blade thickness over relatively lower tip speed ratio for symmetry wing section is relatively smaller than it for asymmetry wing section. $(C_T)_{\max}$ of NACA0025 is largest for the thickness variation. Therefore, $(C_T)_{\max}$ takes the largest value at certain blade thickness. λ at $(C_T)_{\max}$ decreases with the larger blade thickness toward about 1.18 for $t/c = 0.30$.

The torque characteristics reflect to C_P. There is a tendency that C_P roughly increases with the larger blade thickness in a range of 0.6< λ <1.2. In detail, C_P of NACA0025 is largest

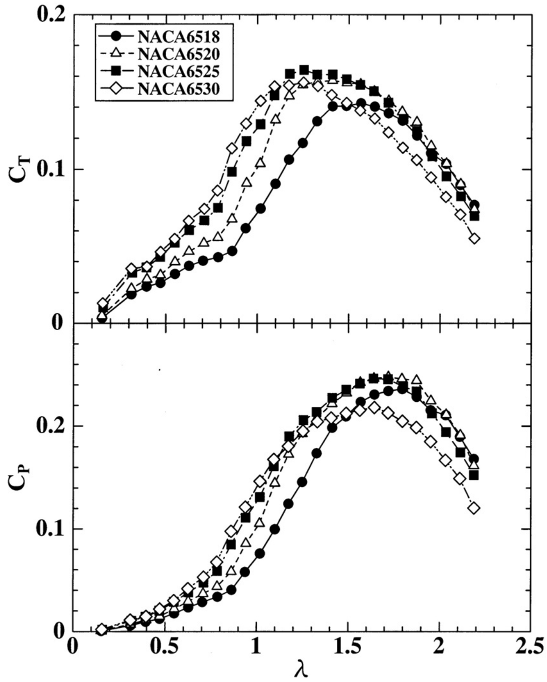


Fig. 4 Effects of thickness on the time mean torque and power characteristics (Asymmetry wing section).

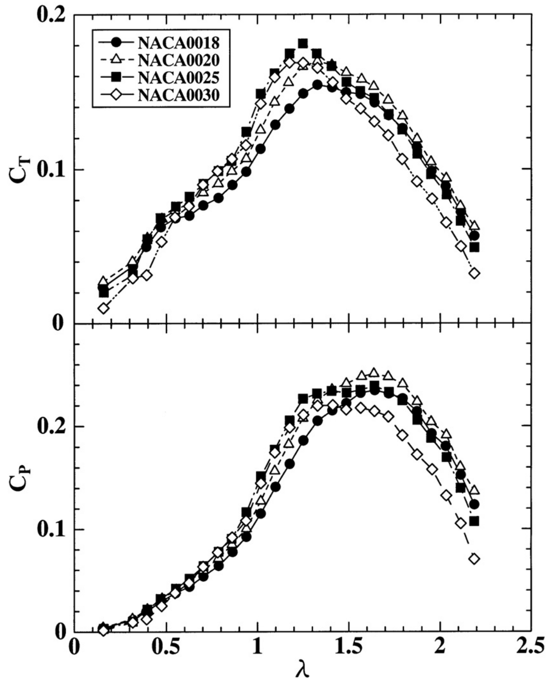


Fig. 5 Effects of thickness on the time mean torque and power characteristics (Symmetry wing section).

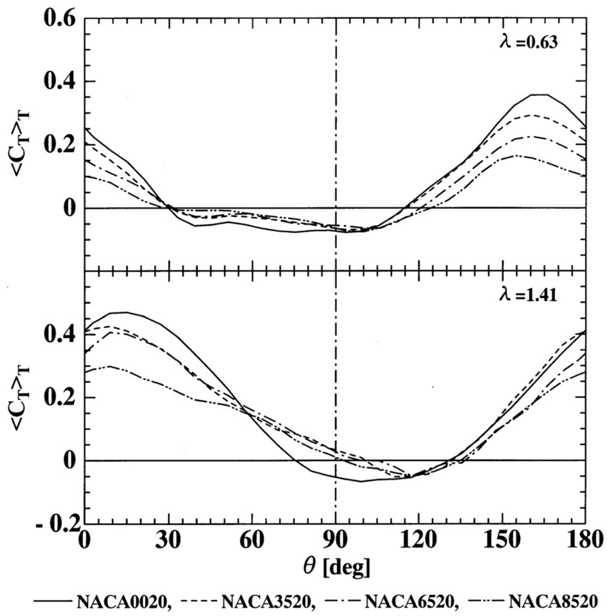
in a range of 0.9< λ <1.4. $(C_P)_{\max} \cong 0.25$ of NACA0020 is largest for the thickness variation. Therefore, $(C_P)_{\max}$ takes the largest value at certain blade thickness. Then λ at $(C_P)_{\max}$ of NACA0030 is about 1.41, and it is smallest in comparison with the others. The curves of C_P of NACA0025 and NACA0030 are comparatively flat around $(C_P)_{\max}$.

4.2. The torque variation

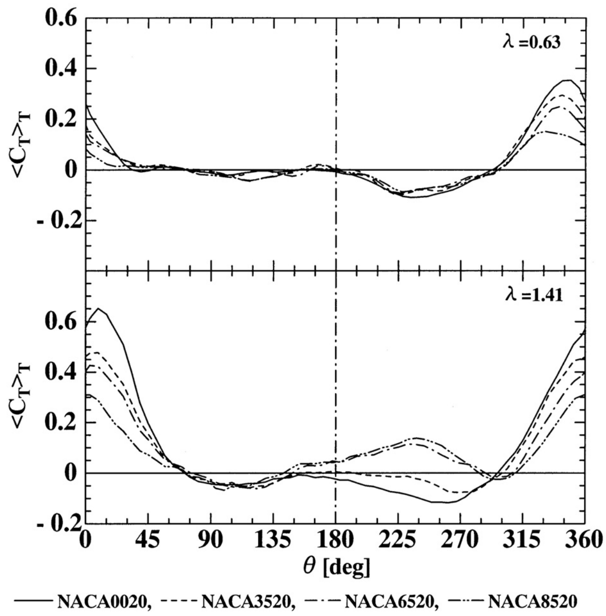
4.2.1. Effects of camber

a. 2-blades case

The torque variation should be investigated to understand effects of camber on the time mean characteristics of the wind turbine. Figure 6(a) is the temporal net torque variation $\langle C_T \rangle_T$ showing effects of camber for 2-blades case at two representative tip speed ratios, λ =0.63 and 1.41. In a range of λ <1, the effect of the camber on the mean torque characteristic is most remarkable at λ =0.63. C_T takes the maximum at λ =1.41. $\langle C_T \rangle_T$



(a) 2-blades case



(b) 1-blade case

Fig. 6. Effects of camber in torque variation

for 2-blades case is shown for $0 \le \theta \le 180$[deg], because the difference of phase for 2 blades is 180[deg]. First in the case of λ=0.63, $\langle C_T \rangle_T$ takes the maximum when the reference blade is located in a range of $155 \le \theta \le 165$[deg]. At that time the other blade is located in upstream, in a range of $335 \le \theta \le 345$[deg]. Here, the upstream is defined in a range of $0 \le \theta \le 90$[deg] or $270 \le \theta \le 360$[deg], and the downstream is defined in a range of $90 < \theta < 270$[deg]. The maximum of $\langle C_T \rangle_T$, $(\langle C_T \rangle_T)_{\max}$, increases significantly with the smaller camber. The minimum of $\langle C_T \rangle_T$, $(\langle C_T \rangle_T)_{\min}$, in a range of $90 \le \theta \le 105$[deg] are almost the same for all cambers. These results suggest that C_T increases with the smaller camber over relatively lower tip speed ratio of λ<1. The peak to peak value of the torque variation increases with the smaller camber.

Next in the case of λ=1.41, $\langle C_T \rangle_T$ takes the maximum when the reference blade is located in upstream, in a range of $10 \le \theta \le 15$[deg]. $(\langle C_T \rangle_T)_{\max}$ increases with the smaller camber like for λ=0.63. But the difference of between NACA3520 and NACA6520 is not large compared with the case of λ=0.63. $(\langle C_T \rangle_T)_{\min}$ in a range of $100 \le \theta \le 115$[deg] is almost the same for all cambers, but $\langle C_T \rangle_T$ of NACA0020 is smallest remarkably in comparison with the others in a range of 60<θ<120[deg]. Therefore, though $(\langle C_T \rangle_T)_{\max}$ of NACA0020 is largest, C_T of NACA0020 is slightly smaller than it of NACA3520.

As mentioned above the camber influences the magnitude of $(\langle C_T \rangle_T)_{\max}$, which influences the magnitude of C_T. Its tendency is remarkable over relatively lower tip speed ratio of λ<1. And for the larger tip speed ratio, decrease of camber, in particular for symmetry wing section NACA0020, results in not only increase of $(\langle C_T \rangle_T)_{\max}$ but also decrease of torque in a range of $60 < \theta < 120$[deg].

b. 1-blade case

1-blade case is shown in Fig. 6(b). In the case of λ=0.63, $\langle C_T \rangle_T$ takes the maximum when the reference blade is located in upstream, in a range of $330 \le \theta \le 350$[deg]. $(\langle C_T \rangle_T)_{\max}$ increases with the smaller camber. $\langle C_T \rangle_T$ are almost the same for all cambers in a wide range of $30 \le \theta \le 300$[deg].

In the case of λ=1.41, $\langle C_T \rangle_T$ takes the maximum when the reference blade is located in upstream, in a range of $0 \le \theta \le 10$[deg]. $(\langle C_T \rangle_T)_{\max}$ increases with the smaller camber like for λ=0.63. A tendency of the torque variation is divided into two cases in a range of 150<θ<300[deg]. One is in a range of $f/c \le 0.03$ (NACA0020, NACA3520), and another is in a range of f/c>0.06 (NACA6520, NACA8520). $\langle C_T \rangle_T$ takes the minimal value in a range of $255 \le \theta \le 270$ [deg] in the former. Otherwise it takes the maximal value at $\theta \cong 240$[deg] in the latter. That suggests that $\langle C_T \rangle_T$ increases with the larger camber in the range of 150<θ<290[deg].

Here we will examine the influence of camber to $(\langle C_T \rangle_T)_{\max}$ for 1-blade. The azimuth angle of the blade of the wind turbine with 1-blade at $(\langle C_T \rangle_T)_{\max}$ is in the range where the lift force acting to the blade most contributes to the rotor torque. In this range it is supposed that $(\langle C_T \rangle_T)_{\max}$ increases with the smaller camber, because the suction side of the wing section is located in the side of rotational axis[11]. Then $\langle C_T \rangle_T$ takes the maximal value at $\theta \cong 240$[deg] in the case of f/c>0.06. At this phase the suction side of the wing section is located in the opposite side of rotational axis[11], in other words the blade takes positive angle of the attack. Therefore, it is thought that the rotor torque increases with the larger camber, because the maximum lift coefficient increases with the larger camber. However, it is necessary that contribution of the drag and the moment is considered in the phase.

Though it is difficult to compare 2-blades case with 1-blade case directly, because of solidity difference, we will try to interpret qualitatively characteristics of $\langle C_T \rangle_T$ on 2-blades case from characteristics of $\langle C_T \rangle_T$ on 1-blade case in the case of λ=1.41. Figure 7 is the torque variation of the wind turbine with 2-blades that is estimated from 1-blade

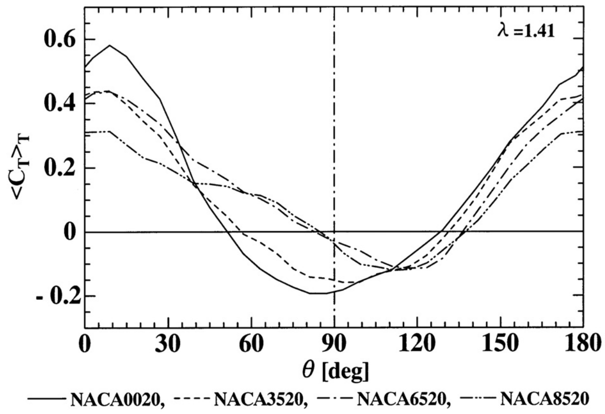


Fig. 7 The torque variation of the wind turbine with 2-blades estimated from 1-blade torque variation

torque variation in Fig.6(b). These torque variations are qualitatively agreed with the temporal torque variation of 2-blades case. Namely, $\langle C_T \rangle_T$ takes the maximum when one of the blades is located in upstream. There is a tendency that $(\langle C_T \rangle_T)_{\max}$ increases with the smaller camber. The significant decreasing torque of 2-blades case of NACA0020 in a range of 60< θ <120[deg] is roughly corresponding with the decreasing torque of the estimated torque of 1-blade case in a range of 45< θ <100[deg]. Because $\langle C_T \rangle_T$ takes the maximum when the reference blade is located in upstream and it increases with the smaller camber for 1-blade, it is understood that $\langle C_T \rangle_T$ takes the maximum when the reference blade is located in upstream and it increases with the smaller camber for 2-blades case. Therefore, it is expected that the torque generated by the blade located in upstream has significant contribution to $(\langle C_T \rangle_T)_{\max}$ on the wind turbine with 2-blades. It follows that remarkable decrease of torque in a range of 240< θ <300 [deg] for 1-blade case with symmetry wing section NACA0020 contributes to significant decrease of $\langle C_T \rangle_T$ of NACA0020 for 2-blades case in a range of 60< θ <120[deg].

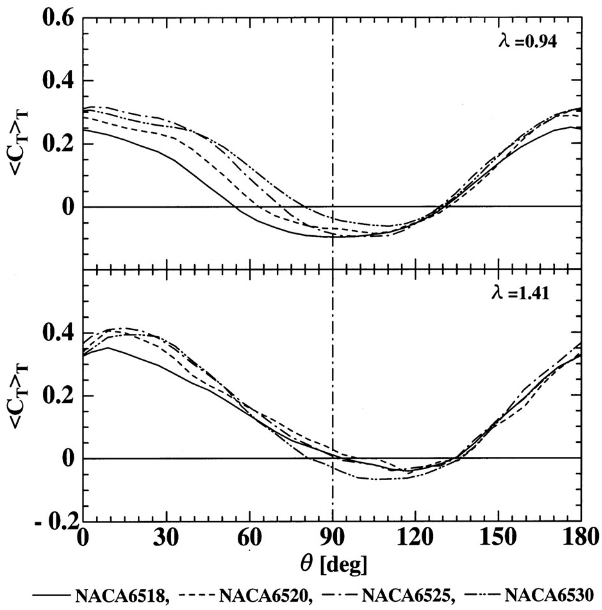
4.2.2. Effects of thickness
(1) Asymmetry wing section
a. 2-blades case

Figure 8(a) is the temporal net torque variation $\langle C_T \rangle_T$ showing effects of thickness in asymmetry wing section for 2-blades case at two representative tip speed ratios, λ =0.94 and 1.41. In a range of λ <1, the effect of the thickness on the mean torque characteristic is most remarkable at λ =0.94. In the case of λ =0.94, $\langle C_T \rangle_T$ takes the maximum when the reference blade is located in $\theta \cong 0$[deg] or $\theta \cong 180$[deg], in other words when one of the blades is located in upstream. There is the tendency that $(\langle C_T \rangle_T)_{\max}$ increases with the larger blade thickness. $(\langle C_T \rangle_T)_{\max}$ of NACA6525 and NACA6530 is almost the same. And in a range of $0 \le \theta \le 120$[deg], there is a comparatively wide range where $\langle C_T \rangle_T$ increases with the larger blade thickness. Regardless of the blade thickness, $\langle C_T \rangle_T$ takes the minimum when the reference blade is located in a rage of $90 \le \theta \le 110$[deg]. $(\langle C_T \rangle_T)_{\min}$ of NACA6530 is largest and of the others is almost the same. What mentioned above correspond that C_T increases with the larger blade thickness in a range of λ <1.

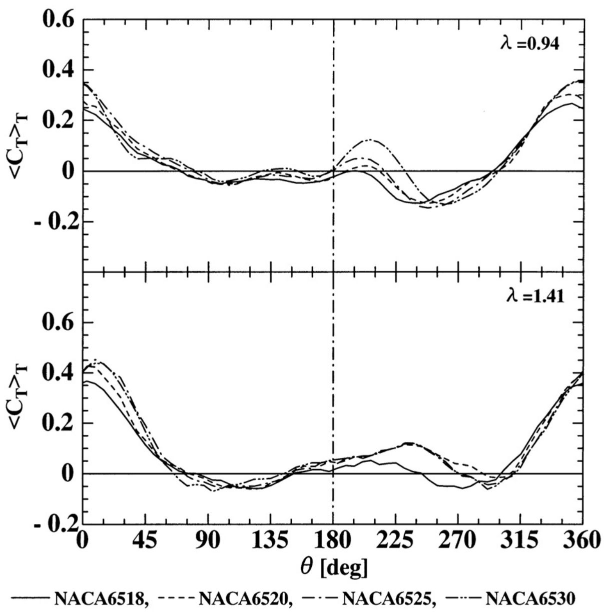
In the case of λ =1.41, the difference of the blade thickness in the torque variation is smaller than it in the case of λ =0.94. That corresponds that the difference of C_T in the blade thickness is smaller than it in the case of λ =0.94. In detail, when the reference blade is located in upstream, in a range of $10 \le \theta \le 15$[deg], $\langle C_T \rangle_T$ takes the maximum. $(\langle C_T \rangle_T)_{\max}$ of NACA6518 is smallest, and the others have a same magnitude. $\langle C_T \rangle_T$ takes the minimum in a range of $105 \le \theta \le 120$[deg]. $(\langle C_T \rangle_T)_{\min}$ of NACA6530 is smallest and of the others is almost the same. And $\langle C_T \rangle_T$ of NACA6530 in a rage of $70 \le \theta \le 130$[deg] is also smallest.

b. 1-blade case

1-blade case is shown in Fig.8(b). In the case of λ=0.94, $\langle C_T \rangle_T$ takes the maximum when the reference blade is located in upstream, in a range of $350 \le \theta \le 355$ [deg]. There is a tendency that $(\langle C_T \rangle_T)_{\max}$ increases with the larger blade thickness. $(\langle C_T \rangle_T)_{\max}$ of NACA6525 and NACA6530 is almost the same. The torque rises in a range of θ>180[deg], and it takes the maximal value in a range of $195 \le \theta \le 210$[deg]. Its maximal value increases with the larger blade thickness. The maximal value of NACA6530 is significantly large. That suggests that $\langle C_T \rangle_T$ increases with the larger blade thickness in downstream, in a range of θ>180[deg]. Regardless of the blade thickness, $\langle C_T \rangle_T$ takes the minimum in a range of $240 \le \theta \le 260$[deg]. $(\langle C_T \rangle_T)_{\min}$ for all thicknesses is almost the same. Because $(\langle C_T \rangle_T)_{\max}$ in upstream and $\langle C_T \rangle_T$ in a range of θ>180[deg] for 1-blade case increase with the larger blade thickness, $(\langle C_T \rangle_T)_{\max}$, when one of the blades is located in upstream, and $\langle C_T \rangle_T$ in a rage of $0 \le \theta \le 120$[deg] for 2-blades case increase with the larger blade thickness. They contribute to increase of C_T with the larger blade thickness in a range of λ<1.



(a) 2-blades case



(b) 1-blade case

Fig.8 Effects of thickness in torque variation (asymmetry wing section)

In the case of λ=1.41, $\langle C_T \rangle_T$ takes the maximum when the reference blade is located in upstream, in a range of $0 \le \theta \le 10$[deg]. $(\langle C_T \rangle_T)_{\max}$ of NACA6518 is smallest. The minimal values of $\langle C_T \rangle_T$ in a range of θ<180[deg] and θ>180[deg] have almost the same value for all thicknesses, but $\langle C_T \rangle_T$ of NACA6518 is significantly small in a range of 165<θ<285[deg]. That is responsible that $\langle C_T \rangle_T$ of NACA6518 for 2-blades case is smallest at the reference blade in a range of $0 \le \theta \le 60$[deg] (the other blade is in a range of $180 \le \theta \le 240$[deg]).

Here we will examine the influence of blade thickness to $\langle C_T \rangle_T$ at representative tip speed ratio of λ=0.94. $(\langle C_T \rangle_T)_{\max}$ in the upstream increases with the larger blade thickness. The azimuth angle of the blade at $(\langle C_T \rangle_T)_{\max}$ for 1-blade case is in a range where the lift force acting the blade most contributes to the rotor torque. In this range the suction side of the wing section is located in the rotational axis side(11). At this moment the blade takes negative angle of attack. Because the larger blade thickness tends to prevent separation on the blade for relatively large negative angle of attack, absolute value of the minimum lift force increases with the lager blade thickness. Therefore, $(\langle C_T \rangle_T)_{\max}$ in the upstream increases with the lager blade thickness. Next we will examined why maximal value of $\langle C_T \rangle_T$ in a range of $195 \le \theta \le 210$[deg] increases with the larger blade thickness. In this range the suction side of the wing section is located in the opposite side of rotational axis(11). At this moment the angle of attack is positive, and the maximum lift coefficient of the wing section increases with the lager blade thickness. It is supposed that the maximal value of $\langle C_T \rangle_T$ in a range of $195 \le \theta \le 210$[deg] increases with the larger blade thickness.

(2) Symmetry wing section

a. 2-blades case

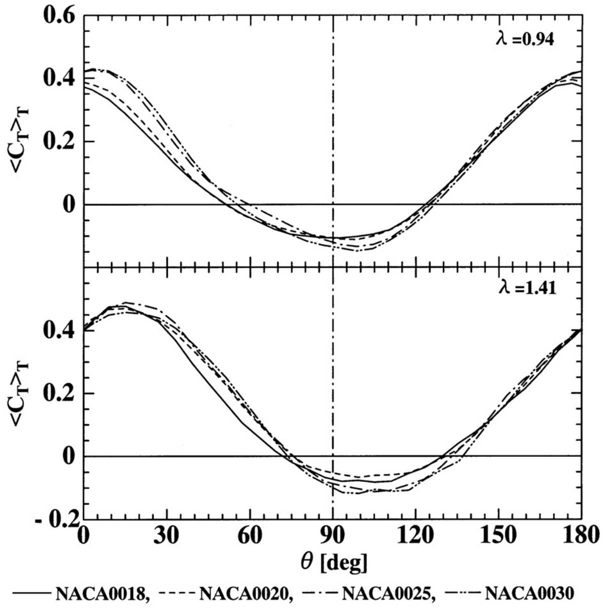
Figure 9(a) is temporal net torque variation $\langle C_T \rangle_T$ showing effects of thickness in symmetry wing section for 2-blades case at two representative tip speed ratios, λ=0.94 and 1.41. In the case of λ=0.94, $\langle C_T \rangle_T$ takes the maximum when one of the blades is located at $\theta \cong 0$[deg] for all thicknesses. There is the tendency that $(\langle C_T \rangle_T)_{\max}$ increases with the larger blade thickness. $(\langle C_T \rangle_T)_{\max}$ of NACA0025 and NACA0030 is almost the same. $\langle C_T \rangle_T$ in a range of $85 \le \theta \le 130$[deg] and $(\langle C_T \rangle_T)_{\min}$ in a range of $90 \le \theta \le 100$[deg] decrease with the larger blade thickness, but their difference are smaller than the difference recognized in $(\langle C_T \rangle_T)_{\max}$. $\langle C_T \rangle_T$ of NACA0025 and NACA0030 are resemble. In detail, $\langle C_T \rangle_T$ of NACA0025 is slightly larger than it of NACA0030 in a wide range of $45 \le \theta \le 165$[deg]. These results indicate that C_T of NACA0025 is largest at λ=0.94. Effects of blade thickness on $\langle C_T \rangle_T$ for symmetry wing section is relatively small compared with that for asymmetry wing section.

In the case of λ=1.41, regardless of the blade thickness, when the reference blade is located in upstream, in $\theta \cong 15$[deg], $\langle C_T \rangle_T$ takes the maximum. The difference of them is small. In detail, $(\langle C_T \rangle_T)_{\max}$ of NACA0025 is largest and $(\langle C_T \rangle_T)_{\max}$ of NACA0030 is smallest. $\langle C_T \rangle_T$ takes the minimum in a range of $95 \le \theta \le 105$[deg], and $(\langle C_T \rangle_T)_{\min}$ of NACA0025 and NACA0030 which have larger thickness are smaller. The difference of $\langle C_T \rangle_T$ on the blade thickness at λ=1.41 is smaller than the result at λ=0.94. That corresponds to smaller effects of the blade thickness on C_T at λ=1.41 in comparison with results at λ=0.94.

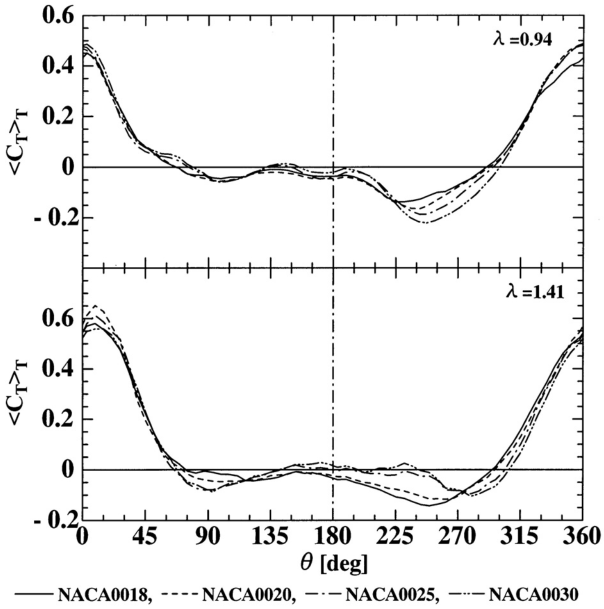
b. 1-blade case

Results in 1-blade case are shown in Fig.9(b). In the case of λ=0.94, regardless of the blade thickness, $\langle C_T \rangle_T$ takes the maximum when the reference blade is located at $\theta \cong 0$[deg]. $(\langle C_T \rangle_T)_{\max}$ of NACA0018 is smallest and of the others are almost the same. $\langle C_T \rangle_T$ decreases significantly in a range of $\theta >$ 195[deg], $\langle C_T \rangle_T$ in a range of $225 \le \theta \le 315$[deg] and the minimal value in a range of $225 \le \theta \le 250$[deg] decrease with the larger blade thickness. It corresponds to decrease of $\langle C_T \rangle_T$ with the lager blade thickness for 2-blades case, when the reference blade is located in a range of $85 \leq \theta \leq 130$[deg] (the other blade is located in a range of $265 \leq \theta \leq 310$[deg]).

In the case of λ=1.41, $\langle C_T \rangle_T$ takes the maximum in a range of $10 \leq \theta \leq 15$[deg]. $(\langle C_T \rangle_T)_{\max}$ of NACA0020 is largest, and $(\langle C_T \rangle_T)_{\max}$ of NACA0030 is smallest. This reflects that $(\langle C_T \rangle_T)_{\max}$ of NACA0030 for 2-blades case is smallest. Effects of blade thickness on C_T over relatively lower tip speed ratio of λ<1 for symmetry wing section is smaller than that for asymmetry wing section. This is reasonable, because effects of blade thickness on $\langle C_T \rangle_T$ for symmetry wing section is smaller than that for asymmetry wing section. As to effects of blade thickness on $\langle C_T \rangle_T$ for symmetry wing section, the lift force acting the blade in upstream dose not become very large for the larger blade thickness, because the lift force is relatively large on the thinner blade for symmetry wing section.



(a) 2-blades case



(b) 1-blade case

Fig. 9 Effects of thickness in torque variation (symmetry wing section)

5. Conclusions

(1) The mean torque and power increase with the smaller camber and the larger blade thickness over relatively lower tip speed ratio of λ <1.

(2) A tendency that C_T increases with the larger blade thickness for symmetry wing section is smaller than it for asymmetry wing section.

(3) $(C_T)_{\max}$ takes the largest value at t/c=0.25, and $(C_P)_{\max}$ takes the largest value at t/c=0.20 in the present experimental variation.

(4) On the effects of camber, $(\langle C_T \rangle_T)_{\max}$ taken at the azimuth angle of the blade located in upstream increases with the smaller camber, and it influences the mean torque coefficient C_T. The tendency is remarkable over relatively lower tip speed ratio. Then for the larger tip speed ratio, $\langle C_T \rangle_T$ in a range of θ>180[deg] also influences C_T, in particular for symmetry wing section, that results in decrease of C_T.

(5) On the effects of thickness in the case of asymmetry wing section, $(\langle C_T \rangle_T)_{\max}$ in upstream and the maximal value of $\langle C_T \rangle_T$ in downstream influence the mean torque coefficient C_T, and there is a tendency that they increase with the lager thickness over relatively lower tip speed ratio.

(6) Effects of blade thickness on the torque variation for symmetry wing section are smaller than it for asymmetry wing section.

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