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Characteristics of flow configurations around side-by-side twin wind blades

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ABSTRACT

The effects of gap ratio (g^*) and angle of attack (α) on side-by-side twin wind blades were investigated in an open-channel wind tunnel. Characteristic wake-flow patterns and aerodynamic performance were analyzed using smoke-streak flow visualization, hot-wire velocimetry, and six-force balancer. Seven smoke-streak flow patterns were defined – attached surface flow, wake instability wave, vortical wake, gap flow, bluff-body wake, anti-phase vortex shedding, and in-phase vortex shedding. For $g^* \approx 0$, the flow characteristics were similar to those of a single wind blade. As g^* increased, these two wind blades induced the vortical wake, gap flow, and anti-phase vortex shedding modes. With further increase in g^*, the wake-flow patterns were similar to those behind a single wind blade. The hot-wire velocimeter detected that the maximum velocity fluctuation occurred at $g^* = 0.083$. This velocity fluctuation decreased toward that of free stream as g^* increased. The vortex-shedding frequency decreased as α increased. For a single wind blade, the maximum lift occurred at $\alpha = 10°$ and the drag increased with α. The pitching momentum increased with α when $\alpha < 45°$. The lift, drag, and pitching momentum on the lower wind blade decreased significantly due to the existence of upper wind blade. The effect of upper wind blade on the lower one deceased as g^* increased.

1. Introduction

The blades of a rotor were driven to rotate when a fluid flows through the rotor. A bluff-body blade caused a pressure difference around the rotor. The inner flow tube in gas turbines, blowers, and air compressors were utilized to generate the pressure difference. In daily applications, fans, wind turbines, and water turbines use the thrust induced from the pressure difference. In these applications, the gap width between the side-by-side blades has a significant effect on the machine performance. The previous study on single blade showed a significant relationship with the surface boundary-layer on the suction side [1–3]. These aerodynamic phenomena included flow separation, reattachment, and vortex formation. In addition, surface flow behavior has a significant effect on wake vortex shedding resulting from the shear instability wave in the boundary-layer separation [4].

Studies on surface flow and aerodynamic performance have showed a laminar boundary layer formed near the stagnation point of a wind-blade leading edge. As the flow moves downstream, the flow separates at the minimum-pressure point. Behind the separation point, the shear layer transits to a turbulent flow. Subsequently, the separated flow reattaches on the wind-blade surface. Between the reattached point and wind-blade trailing edge, the surface flow formed a turbulent boundary layer. A bubble was generated between the separation point and reattached point. At a low chord-length Reynolds number and low angle of attack (AoA), the bubble occupied most of the wind-blade surface. This bubble changes the surface pressure distribution and aerodynamic characteristics. In the 1980s, most studies focused on surface-flow behaviors [5–7]. Lissaman [2] studied flow separation on the laminar boundary layers, boundary-layer transition, and boundary-layer reattachment. He found that the flow separation occurs near the point of the minimum surface pressure. A shear layer evolved downstream and transited to a turbulent flow. The turbulent kinetic energy increases and the separated boundary layer reattached on the wind-blade surface. This reattached turbulent boundary layer extended from the reattached point to the trailing edge.

A study on unstable wake flow revealed that this flow was generated because of the boundary-layer separation and shear-layer instability wave [8]. Research topics included the periodic instabil-

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Nomenclature

b	half wind-blade span, 30 cm
C	chord length, 6 cm
C_L	lift coefficient (= L/qbC)
C_D	drag coefficient (= D/qbC)
C_M	quarter-chord moment coefficient (= M/qbC^2)
d	projection chord length
D	drag
f	wake vortex-shedding frequency (Hz)
g^*	gap ratio (= s/C)
L	lift
M	quarter-chord momentum
q	dynamic pressure of free-stream (= $\rho u_\infty{}^2/2$)
Re	Reynolds number (= $u_\infty C/\nu$)
s	streamwise spacing between the centers of two wind blade cylinders
St	Strouhal number of vortex shedding (= fd/u_∞)
$T.I.$	turbulence intensity
u_∞	free-stream velocity
u	x-component of mean velocity, m/s
u'	x-component of velocity fluctuation, m/s
v	y-component of mean velocity, m/s
v'	y-component of velocity fluctuation, m/s
x	streamwise coordinate originated at leading edge
y	spanwise coordinate originated at the wing root
α	angle of attack
ρ	air density
ν	kinetic viscosity of air

ity wave, the effect of coherent structure on wind-blade performance, and wind vibrations induced by the wake vortex (fluid–structure coupling) [9,10]. Previous studies focused on the wake flow behind a bluff body [11,12]. Roshko [13] found that the Strouhal number ($St = fd/u$) remained constant with values of 0.21, 0.18, and 0.14 for a cylinder, 90° wedge, and plain board, respectively, when the Reynolds number (Re) was in the range $10^3 < Re < 10^5$. In addition, Roshko revealed that St was low for sharp and flat bodies. Huang and Lin [14] used wind and water tunnels to study the instable wake vortex-shedding frequency and behaviors behind wing airfoils. They found that the surface flow did not separate at a low AoA behind a sharp trailing-edge wing. However, such wings have a mixing-layer wake flow and a small-amplitude instability wave. These instability waves evolved into a wake vortex and subsequently a vortex street. Furthermore, in this wake flow, the viscous effect in the boundary layer was considered. At high AoA and high Reynolds numbers, the projection chord-length dominated the instability wake flow. In addition, the periodic vortex frequency displayed two trends: (1) at low Reynolds numbers, St decreases as Re increases, and (2) at high Reynolds numbers, St remains constant. Huang et al. found that St remained constant and Roshko number was proportional to St in the inertia-dominated regime. However, in the viscosity-dominated regime, Roshko number remained constant and St was inversely proportional to Re [15].

In studies on multi-blade patterns, many researchers have numerically simulated flow structures and aerodynamic performance. Dong and Lu [16] used three fish-like profiles to numerically investigate the effect of gap ratio on aerodynamic performance. They found that the gap ratios influenced the formation of in-phase and anti-phase vortex streets. At low gap ratios, the upper and lower vortex series were close and then squeezed to form an anti-phase vortex street. In contrast, the high gap ratio caused an in-phase vortex street. Furthermore, the drag coefficient decreased with gap ratio. Hansen and Madsen [17] employed the blade element momentum method to determine the blade profiles and compute aerodynamic coefficients. Sieverding et al. [18] used a supersonic wind tunnel to study the surface-pressure distribution on side-by-side blades. They found the non-uniform pressure distribution near the blade trailing edge at subsonic speeds. Furthermore, the lowest pressure occurred at the trailing edge. On the suction side, the vortex formed near the trailing edge was influenced by the adjacent blade. Uzol et al. [19] studied a transient flow field by using particle image velocimetry and water tunnel. They found that the free-stream velocity changed by about 13% due to the transverse velocity behind the blades. The gap ratio between blades has a significant effect on blade efficiency.

Previous studies have investigated single bluff bodies and side-by-side cylinders/squares. In this study, the effects of gap ratio and AoA on a single bluff wind-blade and two side-by-side wind blades were investigated. Smoke-streak visualization was employed to observe the characteristic flow patterns. Hot-wire velocimetry was used to measure the wake vortex-shedding frequency and calculate the Strouhal number. Furthermore, the hot wire was used to measure the velocity contour around the wind blades. A six-force balancer was used to measure the aerodynamic loadings.

2. Experimental setup

2.1. Apparatus

Fig. 1 shows the wind tunnel and experimental setup used in this study [20]. This open-loop wind tunnel was operated stably in the range of 1.64–28.28 m/s. This wind tunnel included seven parts: noise-filtering section, steady section (settling chamber), nozzle, test section, vibration absorber, expansion section (diffuser), and blower fan. The noise-filtering section comprised two parts: (1) an aluminum-made honeycomb for eliminating transverse flow fluctuations, and (2) a three-layer metal mesh for filtering the longitudinal flow noise. The nozzle contraction ratio was 3.24:1. The cross-section area and length of the test section were 50×50 cm^2 and 120 cm, respectively. The downstream test section was connected to a vibration absorber, which was used to isolate the operation vibrations of the blower fan. The downstream expansion section was connected to a centrifugal blower fan driven using a three-phase and 20 horse-power motor. The motor rotation speed was adjusted using a inverter with the maximum rotating speed of 1160 rpm. The precision of inverter is 0.1 Hz and the operable range is 0–60 Hz, which corresponds to a flow speed of 1.64–28.28 m/s.

2.2. Blades

An NACA 00122 [21] aerofoil was used to investigate the flow behavior. This wind blade was fabricated using solid chrome moly 4340 to reduce the wind resonance. The chord length (C) and wind-blade span (S) were 6 and 30 cm, respectively; and therefore, the aspect ratio was 5. The wind-blade surface was polished for reducing the surface roughness. An index plate was used to rotate the