Fundamental Study on Improvement of Performance of Wells Turbine Blade

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Abstract. In the present paper the attention is focused on the effect of the dimples on the stall characteristics and aerodynamic sound radiated from two-dimensional airfoil. In general, two-dimensional blade is used as the airfoil of Wells turbine. We measured the lift force acted on the airfoil and aerodynamic sound. The dimples were effective to improve the stall characteristics. As the dimple diameter and number of dimples increased, the broadband noise at higher frequency component increased slightly compared with normal airfoil. The dimples were not effective to reduce the broadband noise radiated from airfoil. In contrast, the dimples were effective to reduce the discrete tone noise radiated from airfoil. This noise depended on the geometry, position and number of dimples. The suitable geometry, position and number of dimples were discussed to improve the stall characteristics and reduction of aerodynamic sound.

1. Introduction
The Wells turbine is a self-rectifying air turbine that is expected to be widely used in wave energy devices with oscillating water columns (OWCs) [1-4]. Wells turbine is composed of the cascade of blades arranged to the rotational axis. The noise is a serious problem when large-scale versions of these machines are operated because they rotate at high speeds. The noise evaluation will become an inescapable problem in order to put wave power plants to practical use.

It is generally known that the tonal noise is generated from two-dimensional airfoil at certain flow conditions at a discrete frequency about 30 dB above the background broadband level. This discrete tone noise is occasionally generated from gliders and small aircrafts, etc. Many studies have been published on the characteristics and occurrence mechanisms of this noise [5-13]. In addition, there are many studies to reduce the aerodynamic noise radiated from the airfoil [14-21]. Fukano et al. also reported that the fan noise decreased by changing the profile of rotor blade [14]. Polacek et al. showed that the wavy-leading-edge was effective to reduce the noise [15]. Nishimura et al. observed that the fan noise reduced to affix a fur material around leading edge on the surface of wing for cooling fan [16]. Hamakawa et al. showed that the local porous material on the surface of airfoil was effective to reduce the aerodynamic noise [19].

On the other hand, Takasaki et al. showed the improvement of stall margin of Wells turbine by introducing the chevron-shaped notch-cut trailing edge [22]. Hamakawa et al. have clarified the effect
of serrations, dimples or plasma actuator on aerodynamic noise radiated from two-dimensional airfoil [19-21][23]. However, the suitable methods to improve the stall characteristics and reduce the aerodynamic noise radiated from Wells turbine were not clear in detail.

The purpose of the present study is to clarify the effect of dimples on the stall characteristics and aerodynamic sound radiated from two-dimensional airfoil used Wells turbine. The suitable geometry, positions and minimum number of dimples are discussed to improve the stall characteristics and reduction of aerodynamic sound.

2. Experimental Apparatus and Procedure
Our experiments were performed in a low-noise wind tunnel, which has been described in detail elsewhere [19-21][23][24]. This wind tunnel was an open-circuit with wing-type silencers in the diffuser located at the outlet of the blower and splitter-type silencers at the inlet of the blower. The test section was placed in the anechoic room, which was rectangular in shape, and 3 m long, 3 m wide, and 3 m high. The collector was downstream of the test section. Noise-absorbing furry materials were attached to the surface of the collector to reduce the interaction noise between the open jet and the collector. This collector was connected to a 3-m-long sound absorbent duct. The background noise was about 63 dB(A) at a freestream velocity of 50.0 m/s.

Figure 1 shows a schematic view of the test-section and a test airfoil. The cross section of the nozzle exit was a 0.5-m-wide and 0.25-m-high square. A test airfoil was installed in the test section 100 mm downstream of the nozzle exit. The freestream velocity ranged from 20 m/s to 40 m/s at the test section inlet. The Reynolds numbers, based on the chord length, \( Re \), and freestream velocity, \( U_\infty \), ranged from \( 1.3\times10^4 \) to \( 3.0\times10^5 \). The flow past the nozzle was uniform, and the drift of the freestream velocity was less than about 0.9 %. The freestream turbulence level was less than 0.5 % of the freestream velocity. In addition, no peak of velocity fluctuation spectrum at the test section without the test airfoil was formed at this velocity range. Two end plates were placed at the top and bottom of the test section, and a test airfoil was placed vertically and rigidly supported between them. These were 900-mm-wide and 450-mm-long acoustically non-reflecting end plates, which were large enough to cover the jet edge region. The downstream distance from the test airfoil to the edges of the end plates was 350 mm. These end plates were composed of a 25-mm-thick polystyrene and 25-mm-thick glass wool backed with a punched steel plate to reinforce the plate rigidity [24]. It was clearly observed that the results for the non-reflecting end plates were almost the same as the attenuation characteristics of the free field.

Figures 2 shows the test airfoil. The dimples were mounted near the trailing edge of test airfoil as shown in Fig. 2. The pitch of dimples, \( b \), are 6.3 mm and 12.6 mm. The depth, \( a \), was 13 mm and 20 mm. The airfoil has NACA0015 profile, the chord length, \( l \), is 100 mm and span length, \( h \), is 250 mm. We measured SPL at attack angles, \( \alpha=0 \) and 4 degree. The features and symbols are presented in Table 1.

![Figure 1. Schematic of test section][19-21][23].  ![Figure 2. Schematic of test airfoil with dimples][23].
Table 1. Geometry of test airfoil.

| Feature        | a mm | b mm | Features                                      |
|----------------|------|------|-----------------------------------------------|
| Dimples        | 13   | 12.6 | Pressure side or Suction side, \( d=3, 6, 9 \)mm, \( n=20 \) |
| Dimples        | 13   | 6.3  | Pressure side or Suction side, \( d=3 \)mm, \( n=40 \) |
| Serrations[20] | 13, 20 | 6.3, 12.6 |                                      |
| Normal         | -    | -    | -                                             |

The aerodynamic sound in the far field was measured at 500 mm from the test airfoil using a microphone. When the observation location was far enough to be considered as the far field, the effect of the near field could be neglected. Measurements of the lift force on the test airfoil was performed using a load cell and amplifier. One side of the load cell was supported at the edge of the test airfoil, while the other side was fixed at the mass bed. The other side of the test airfoil was a free edge.

3. Results and Discussion

3.1. Effect of dimples on lift coefficient

We measured the lift force acted on the test airfoil. Figure 3 shows the lift coefficient against the attack angle, \( \alpha \). Fig. 3(a) is the variation of dimples diameter on lift coefficient, \( C_L \). The dark dotted line in Fig. 3(a) is the baseline result of normal airfoil. As \( \alpha \) increased, \( C_L \) also increased proportionally. As \( \alpha \) increased more, \( C_L \) decreased rapidly at \( \alpha=13 \) degree. The reduction of \( C_L \) is caused by the stall of test airfoil. The stall attack angle is \( \alpha=13 \) degree for normal airfoil. The stall attack angles became \( \alpha=14 \) degree for the three cases of suction side dimples of \( d=3 \) and 6 mm, and pressure side dimples of \( d=3 \) mm. It is clear that the stall attack angle increased to introduce the dimples on the surface of airfoil. The dimples were the effective to improve the stall characteristics. The red dotted line in Fig. 3(a) is the result of serrations[23]. The stall attack angle became \( \alpha=15 \) degree. The stall attack angle of serrations was larger than that of dimples. The trailing edge serrations were also effective to improve the stall characteristics. This is the same tendency of Wells turbine with the chevron-shaped notch-cut trailing edge [22].

Fig. 3(b) is the variation of dimples position on \( C_L \) of \( n=40 \). The stall attack angles became \( \alpha=15 \) degree for the two cases of \( n=40 \). The stall attack angle of serrations was agreed well with that of dimples of \( n=40 \).

From the above discussions, it is clear that the dimples are effective to improve the stall characteristics of two-dimensional airfoil. It is considered that the stall margin may increase to introduce the dimples on rotor blade of Wells turbine.

![Figure 3. Comparison of lift coefficient (\( Re=2.6\times10^5 \)).](chart)

(a) Variation of dimples diameter on \( C_L \)  
(b) Variation of dimples location on \( C_L \)
3.2. Effect of dimples on aerodynamic sound

First, we measured the aerodynamic sound radiated from normal airfoil [19-21][23]. Multiple peaks observed in the spectrum of SPL at \( a=0 \) and 4 degrees. The peak frequencies were dependent on the freestream velocity \( U_\infty \). For small variations in the freestream velocity, the frequencies of these sounds were approximately proportional to \( U_\infty^{0.8} \). At intermittently spaced freestream velocities the frequency of the sound was observed to jump to other curves proportional to \( U_\infty^{1.5} \). The frequency of the sounds against the freestream velocity had a ladder-like structure with rungs of curves proportional to \( U_\infty^{0.8} \). These are same tendency for Paterson et al. [5].

The spectra of SPL of the aerodynamic sound radiated from the test airfoils with dimples were measured. Figure 4 shows the variation of dimples diameter on spectra of SPL for attack angle of \( a=4 \) degree. Fig. 4(a) is the result of dimples mounted on the suction side of airfoil. Multiple peaks were clearly observed in the spectrum for dimples of \( d=3 \) and 9 mm. However, no peaks were observed in the spectrum of \( d=6 \) mm. Fig. 4(b) is the result of the pressure side. Multiple peaks were observed in the spectrum for all cases. It is considered that the optimum geometry, position and number of dimples may be existed.

Fig. 5 is the variation of number of dimples on spectra of SPL. Figs. 5(a) and (b) are the results of dimples mounted on the suction and pressure sides of airfoil, respectively. No peaks were observed in the spectrum for dimples mounted on the suction and pressure sides of \( d=3 \) mm, \( n=40 \).

From above discussions, it is clear that the dimples were effective to reduce the discrete tone noise radiated from airfoil. This noise radiated from airfoil depended on the geometry, position and number of dimples. It is considered that the dimples of suction side, \( d=3 \) mm, \( n=40 \) are effective to reduce the discrete tone noise radiated from airfoil. The discrete tone noise may decrease to introduce the dimples on rotor blade of Wells turbine.

On the other hand, the discrete tone noise may not occur at the Wells turbine, because the relative velocity of rotor blade change from the hub to tip region of Wells turbine. If the discrete tone noise does not occur, the reduction of broadband noise become more important.

Fig. 6 is the variation of Reynolds number on spectra of SPL of \( a=0 \) degree. Figs. 6(a) and (b) are the results of \( Re=1.3\times10^5 \) and \( Re=2.5\times10^5 \), respectively. Multiple peaks were observed in the spectrum of \( Re=1.3\times10^5 \). As the dimples diameter increased, the broadband noise over 1000 Hz increased slightly with the exception of multiple peaks. In contrast, no high peaks were observed in the spectrum of \( Re=2.5\times10^5 \). The broadband noise over 1000 Hz for dimples increased slightly compared with normal airfoil.

Fig. 7 is the variation of number of dimples on spectra of SPL. As the number of dimples increased, the broadband noise over 1000Hz increased slightly with the exception of some peaks. This is caused by the increase of turbulence in the boundary layer on the surface of the test airfoil.

**Figure 4.** Variation of dimples diameter on spectra of SPL

\( (a=4^\circ, a=13\text{mm}, b=6.3\text{mm}, n=20, Re=1.3\times10^5) \).
From above discussion, it is clear that the dimples are not effective to reduce the broadband noise radiated from airfoil. If there is anything to say, the dimples of suction or pressure side, \(d=3\) mm, \(n=20\) are effective in a slight increase the broadband noise.

4. Conclusions
The effect of dimples on the stall characteristics and aerodynamic sound radiated from two-dimensional airfoil were experimentally investigated in present experimental conditions. As a result, the following conclusions were obtained.
The suction side and pressure side dimples were the effective to improve the stall characteristics of two-dimensional airfoil. It is considered that the stall margin may increase to introduce the dimples on rotor blade of Wells turbine.

The dimples were effective to reduce the discrete tone noise radiated from airfoil. The discrete tone noise radiated from airfoil depended on the geometry, position and number of dimples. The suitable geometries of noise reductions were on the suction side of blade, $d=3$ mm and $n=40$. The noise may decrease to introduce the dimples on rotor blade of Wells turbine. The suction side dimples of $d=3$mm, $n=40$ was most effective to reduce the discrete tone noise and to improve the stall characteristics in present experimental conditions.

As the dimple diameter and number of dimples increased, the broadband noise over 1000 Hz increased slightly compared with normal airfoil. The dimples were not effective to reduce the broadband noise radiated from airfoil. It is considered that the dimples of suction or pressure side, $d=3$ mm, $n=20$ are effective to improve the stall characteristics in a slight increase the broadband noise.

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