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Development of Maple Seed-Type Micro Wind Turbine toward a Sustainable Society

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Abstract

The challenge of harvesting wind power energy using small wind turbines has been a focus for urban and rural areas. This study presents a method for feasibly and safely harnessing wind in urban and rural built environments utilizing micro (168-mm rotor diameter) turbines that can be easily produced with lightly bent maple seed-type flat blades reclined downstream. The reclination reduces noise and enhances the strength of the blade against the wind. We conducted a wind-tunnel experiment to demonstrate optimization of the blade's performance through the power coefficient C_p to tip-speed ratio λ, which provide maximum 0.08 for C_p and not more than 3 for λ. By varying the propeller shape, arrangement of the blades, etc., we were able to clarify an optimized design suitable for built environments, relevant to the UN's Sustainable Development Goals (SDGs). Our findings provide a perspective on the potential for harvesting reliable wind power in urban or rural areas while maintaining an aesthetic architectural appearance.

Keywords

Wind Energy, Micro-Scale Wind Turbine, Maple Seed, Renewable Energy, SDGs, Power Coefficient

1. Introduction

The development of renewable energy resources, such as solar, wind, hydro, storage, and biomass energies, is needed to resolve global energy poverty, climate change, and socioeconomic disparities [1]. Various strategies and policies aim to meet the targets laid out by the UN's Sustainable Development Goals (SDGs) for renewable energy [2]. Current research has focused primarily on methods for integrating renewable energy forms into hybrid energy systems [3]. This has brought about acceleration in the development of resilient energy resources for enhancing

affordable and effective electricity, which is critical for remote regions such as rural areas, where it can alleviate energy poverty [4].

Wind power is a practical and proven technology, developed and used by humans for millennia, as may be seen in the classical windmills of Europe and America [5]. More recently, they have been incorporated into smart grids, where they are integrated with other energy sources such as solar panels [6], and deployed onshore or offshore [7]. This paper focuses on wind energy, specifically small, low-speed wind turbines, categorized as micro wind turbines, less than 0.2 m in rotor diameter, with a 0 - 2 tip-speed ratio λ, and a 0.05 - 0.15 power coefficient C_p [8]. This is because advancing the design and performance of small wind turbines are critical to harnessing decentralized wind energy in urban areas [9], and for improving the aerodynamic characteristics and operational stability of systems in low-wind areas [10]; these facts have led to substantial research [11].

Wind turbines, including micro turbines, face challenges that must be resolved, including noise, safety, and efficiency. The first, low-frequency noise that many find annoying, depends on the synergetic interaction between aerodynamic phenomena around the wind turbine and its mechanical performance [12] [13]. Safety studies have predominantly focused on enhancing blade strength [14] [15]. Meanwhile, efficiency is a fundamental issue that can be addressed by generating electric power with low-speed wind with optimized airfoil or turbine performance. To address these issues, Shimada investigated the performance of state-of-the-art wind turbines with maple seed-shaped blades mimicking the shape of a Japanese toy, with a slightly bent flat plate reclined downstream [16]. This simple structure has the merit of eliminating the cumbersome production process of current propeller type blades. The reclination serves to reduce noise and enhance blade strength, due to the prevention of a vortex generated around the blade, as demonstrated visually and by numerical analysis in our previous study [16]. In addition, as our findings revealed that the design results in a dual-mode possessing characteristics of both lift and drag, it is feasible for use in low-speed wind. The C_p of this turbine with 75-mm long blades was shown to be superior to a propeller-type blade. Furthermore, this wind turbine could be used in isolated or rural areas for small-grid power systems.

The previous study has demonstrated the physical mechanisms of the high performance of C_p in low-speed wind and the merits on the reducing noise and enhancing strength. The aim of the present study is the effect of the blade shape on C_p. This study sought to optimize the performance of maple seed-shaped micro blades in social life. Our findings would contribute to the development of social sustainability by harvesting renewable energy from natural resources.

2. Experiments

As mentioned above, our maple seed-shaped wind turbine mimics the movement

of a simple Japanese toy that falls with a rotational motion; the principle is thus provided by biomimetic techniques. It is structured using two opposable bent flat papers with an angle between them. As a result, these flat plates have the configuration of being bent slightly and reclined downstream. Therefore, no complicated process is needed to produce the blades compared to the current propeller-type blade, which requires cumbersome work. Details regarding the turbine's configuration are available in our previous study [16].

These micro wind turbines were positioned in a wind tunnel with a 20-cm square wind area, as shown in **Figure 1(a)**, and the electric power was measured with a generator labeled "A" in the figure. C_p was obtained from the electrical output from the generator. The generator in the wind turbine had strong magnetic force despite its miniature size (about a 2-cm diameter with a rotating neodymium magnet inside a coil wound by 100-m ultrafine 0.05 mm electric wire) (Otonaokagaku, Vol. 18, Gakken Inc., Tokyo, Japan). Owing to the structure of the strong magnet, the reduction of the generator losses can be realized to be minimized ultimately. The measuring system was the same as that used in our previous study [16]. The turbine blade was positioned so as it was not moved by wind direction. The wind distributions both inside the wind tunnel and just outside of the outlet were confirmed to be the same (an example is shown in **Figure 1(b)**) [17]. The wind velocity was measured with a Pitot tube joined to a manometer (DMP301N12, Okano Works, Ltd. Co., Osaka, Japan). The rotational speed of the blade was measured with a tachometer (HT-5500, Ono Sokki Co. Ltd., Yokohama, Japan). λ was calculated with the mean wind velocity at this distribution. The wind turbine was installed with its blades at the center of the wind distribution, and we confirmed they were not affected by the boundary layer from the inner wall of the wind tunnel. The uncertainty of the measured data was less than 8%, which does not depend on the boundary layer but on the nonuniform distribution of the wind as **Figure 1(b)**. The measuring repeat counts were 8 - 10 times. Wind speed distribution deviation was less than ±1.5%, and turbulence intensity was less than 0.75% RMS.

The blades, made of aluminum and 73 mm in length, were aligned in two different stages cases: a single stage (**Figure 2(a)**); and a double one (**Figure 2(b)**). The latter stage had the blades positioned to avoid overlapping on the front and back sides (**Figure 2(c)**). The blades were installed on the rotational axis as shown in **Figure 2(d)**, with two different types of blades attached parallel and perpendicular to the axial body. The former type was L-shaped (L type) and the latter S-shaped (S type). These blades were installed at various angles to the axis. The final design is shown in **Figure 2(e)**. The blade shapes and dimensions were varied, as shown in **Figure 3**: straight or bent at the edge of the blade; narrow or wide blade width; diverging or tapering off blade edge. For comparison to the maple type blade, ordinary propeller types were used as shown in **Figure 3(k)** and **Figure 3(l)**. We investigated the effect of the configuration of the blade on the wind turbine properties.

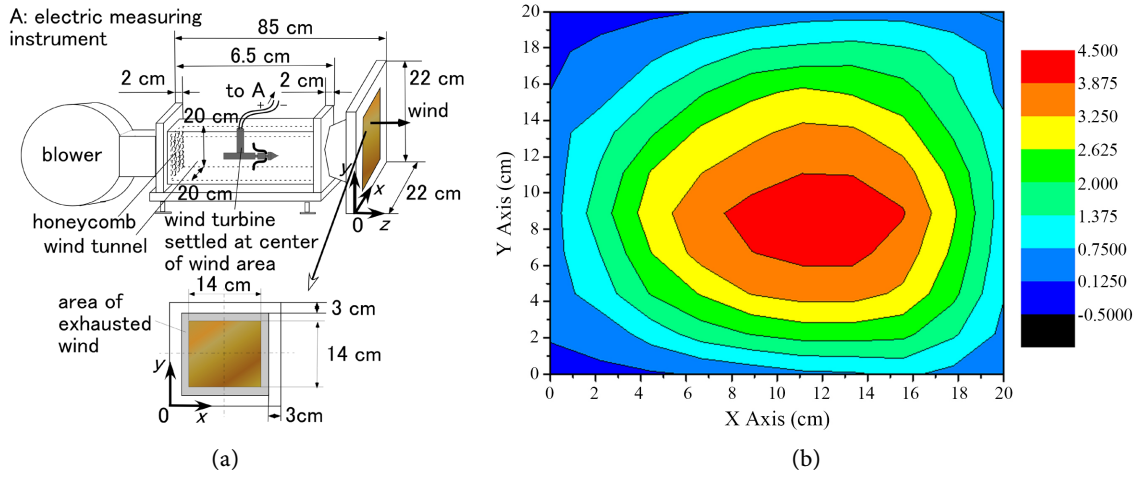


Figure 1. Overview of the experiment [17]: (a) schematic diagram of wind turbine in wind tunnel; (b) wind distribution by wind tunnel at 4.8-m/s mean wind velocity at $z = 3$ cm.

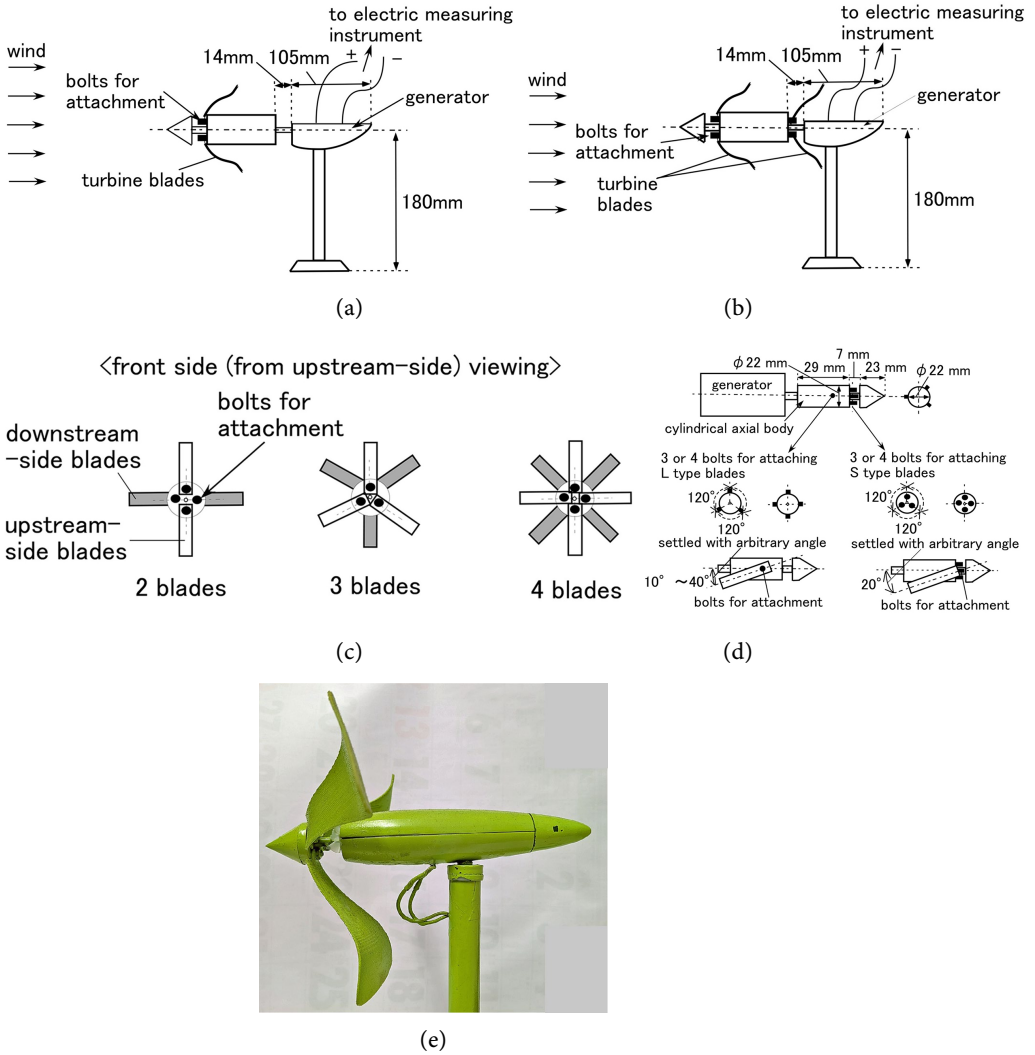
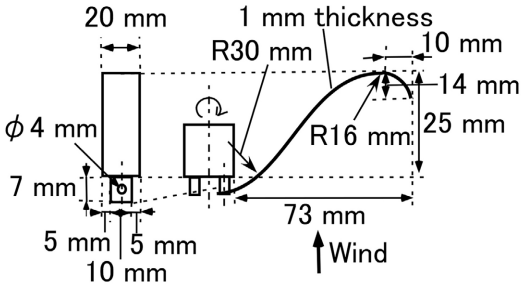
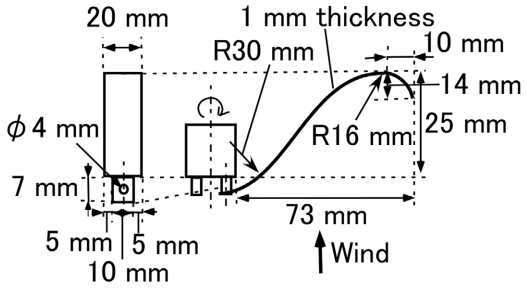


Figure 2. Wind turbine and blade positioning [17]: (a) wind turbine with single stage; (b) wind turbine with double stage; (c) the arrangement of blades in double stage; (d) installation of blades; (e) image of wind turbine.


20 mm
1 mm thickness
R30 mm
10 mm
14 mm
25 mm
R16 mm
ϕ 4 mm
7 mm
73 mm
5 mm
5 mm
10 mm
Wind

(a)


20 mm
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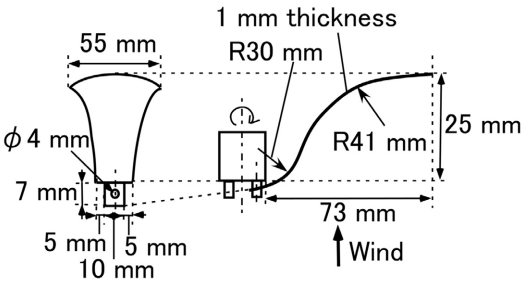
R16 mm
ϕ 4 mm
7 mm
73 mm
5 mm
5 mm
10 mm
Wind

(b)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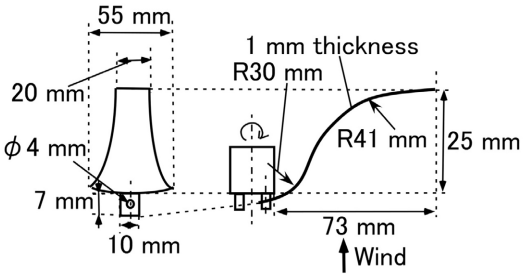
1 mm thickness
R30 mm
25 mm
R41 mm
ϕ 4 mm
7 mm
73 mm
5 mm
5 mm
10 mm
Wind

(c)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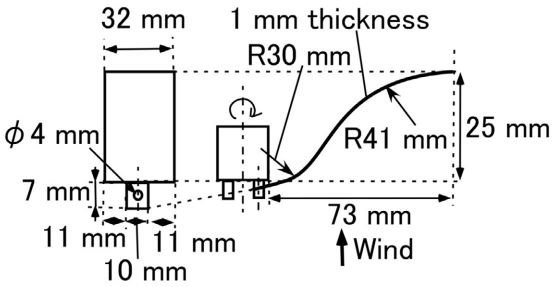
R30 mm
20 mm
25 mm
R41 mm
ϕ 4 mm
7 mm
73 mm
10 mm
Wind

(d)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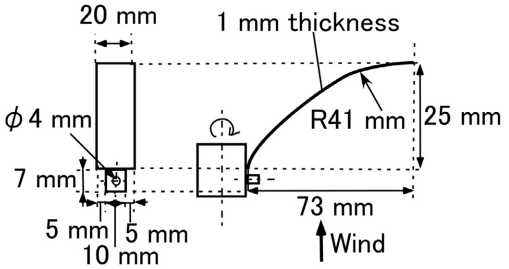
11 mm
11 mm
10 mm
Wind

(e)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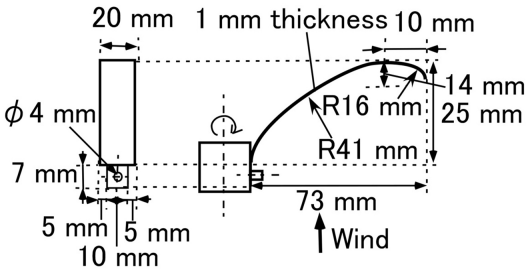
Wind

(f)


20 mm
1 mm thickness
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R16 mm
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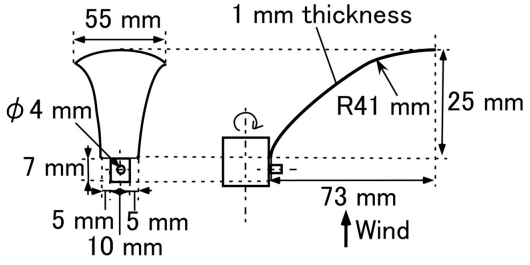
R41 mm
ϕ 4 mm
7 mm
73 mm
5 mm
5 mm
10 mm
Wind

(g)


55 mm
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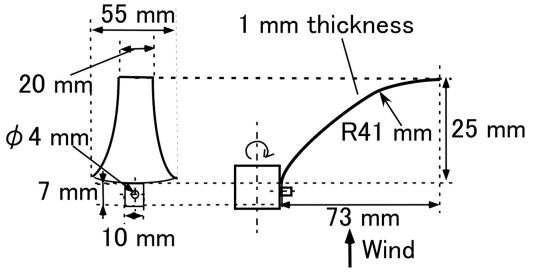
73 mm
5 mm
5 mm
10 mm
Wind

(h)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25 mm
R41 mm
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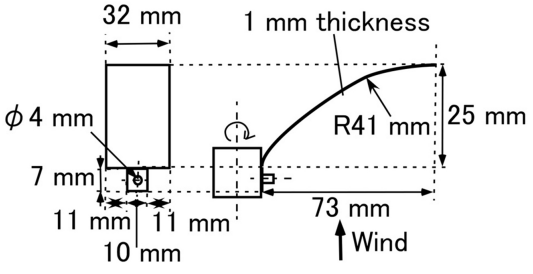
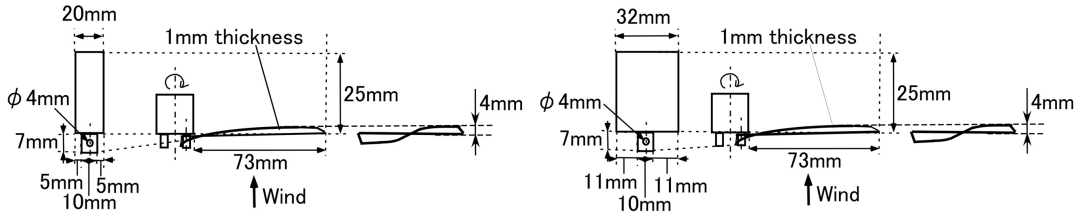
73 mm
10 mm
Wind

(i)


32 mm
1 mm thickness
ϕ 4 mm
25 mm
R41 mm
7 mm
73 mm
11 mm
11 mm
10 mm
Wind

(j)

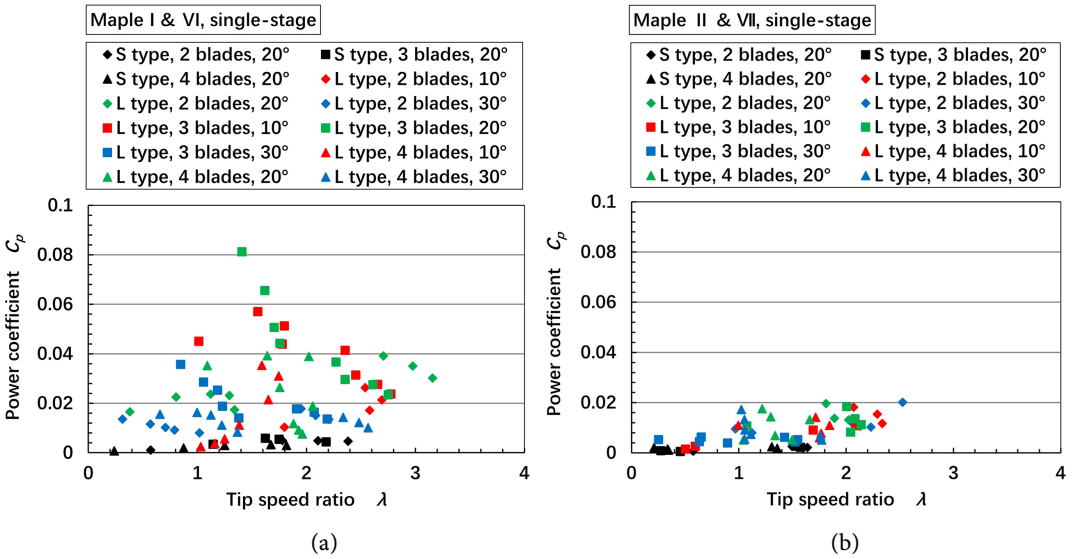


(k) (l)

Figure 3. Schematic diagram and dimensions of turbine blade [17]: (a) Maple I; (b) Maple II; (c) Maple III; (d) Maple IV; (e) Maple V; (f) Maple VI; (g) Maple VII; (h) Maple VIII; (i) Maple IX; (j) Maple X; (k) Propeller I; (l) Propeller II; (a)-(e) S type; (f)-(j) L type; (a), (b) comparison between straight and bent edge of the blade as for S type; (f), (g) comparison between straight and bent edge of the blade as for L type; (b), (e) comparison between narrow and wide width of the blade as for S type; (f), (j) comparison between narrow and wide width of the blade as for L type; (c), (d) comparison between diverging and tapering off edge of the blade as for S type; (h), (i) comparison between diverging and tapering off edge of the blade as for L type.

3. Results and Discussion

Figure 4 presents the properties from low to high wind-speed range. For a range of less than 4-*I*, the wind speed was less than 18-m/s. A comparison of L and S types showed that the C_p to I of the L type blade was larger than that of the S type blade. In terms of the attachment angle of the blades, it can be seen that the 20-degree angle of attachment had the largest C_p to I of all angles. Regarding blade shape, C_p to I in the case where the blade had a bent edge was larger than when the edge was straight for both S and L types. Meanwhile C_p to I for the wider blade was larger than for the narrow one in both S and L types; in addition, C_p to I for the diverging blade edge was larger for the tapered off one for both S and L types. These results are dependent on solidity, defined by the ratio of the projected area of the blade and area scanned by the blade. Our experimental results are due to high solidity, which induces the drag-type wind turbine. They also indicate optimization of the maple-seed blade performance.



(a) (b)

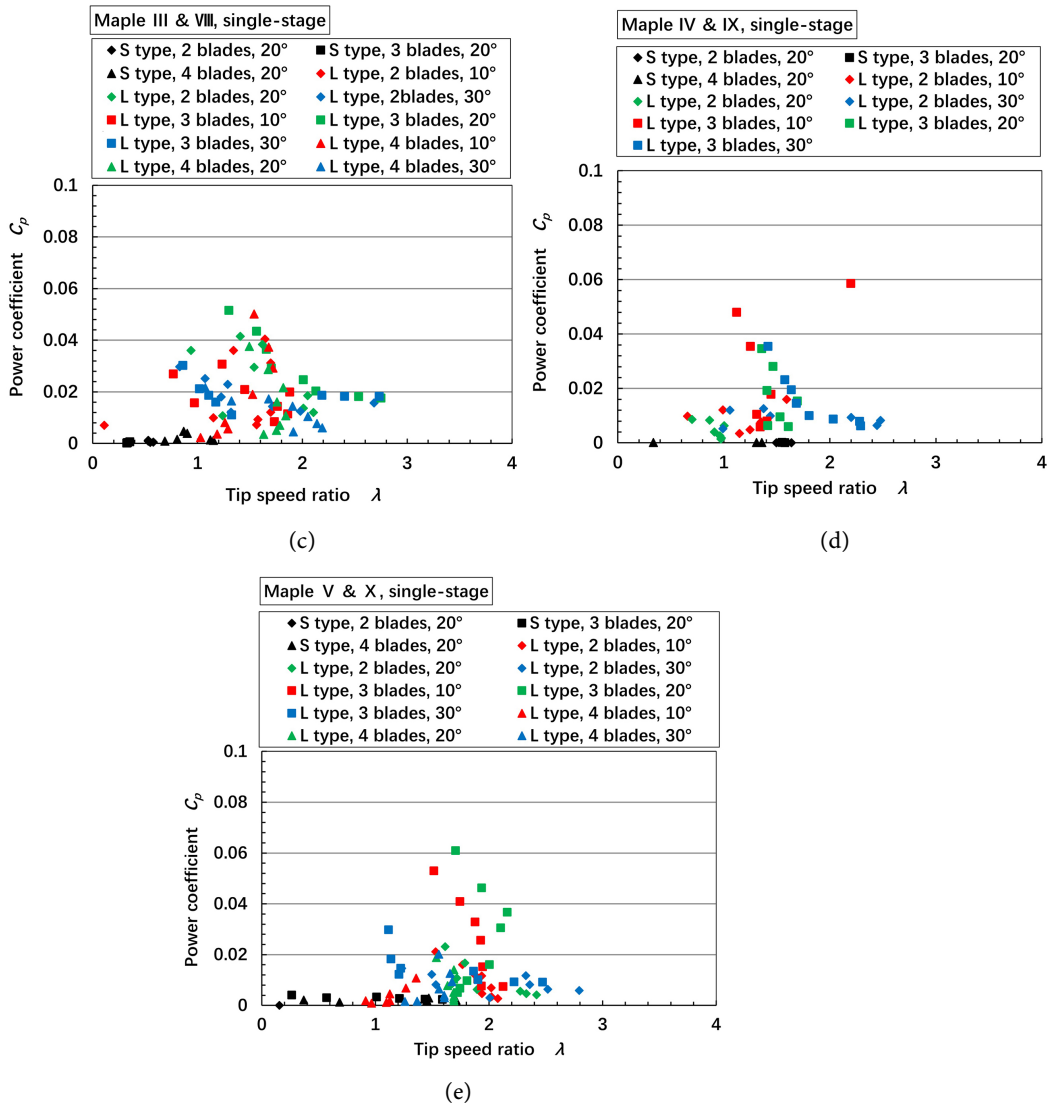


Figure 4. C_p to λ in cases of single-stage maple seed type from low to high wind speed: (a) Maple types of I and VI; (b) Maple types of II and VII; (c) Maple types of III and VIII; (d) Maple types of IV and IX; (e) Maple types of V and X.

Figure 5 shows the properties at low wind speed (for a range of less than 2-λ, the wind speed was less than 5-m/s). Typical findings indicate that the C_p to λ of the maple-seed turbine was larger than the propeller type even for low wind speed, which confirms the findings of our previous study [16]. On the other hand, in the case of 2 or 3 blades, C_p to λ of the single stage turbine was larger than that of the double stage. This was due to the blades creating turbulence when their number increased, as in the case of double stage or 4 blades. Regarding blade shape, although the difference of C_p was unclear, that of λ was evident: (i) λ in the case of a bent edge blade propeller was larger than that of a straight one regardless of whether it was S or L type, and the stage type; (ii) λ in for a wide blade was larger than that with a narrow one regardless whether it was S or L type, and the stage type; and (iii) λ with a blade with diverging edge was larger than a blade with a

tapering one regardless of whether it was S or L type, and of stage type, except for 2 blades and single stage. Because λ connotes the rotational speed of the wind turbine, the rotation varied by these conditions. As for C_p, the tendency was provided in Figure 4. These results indicate we were able to optimize the performance of the maple-seed blade.

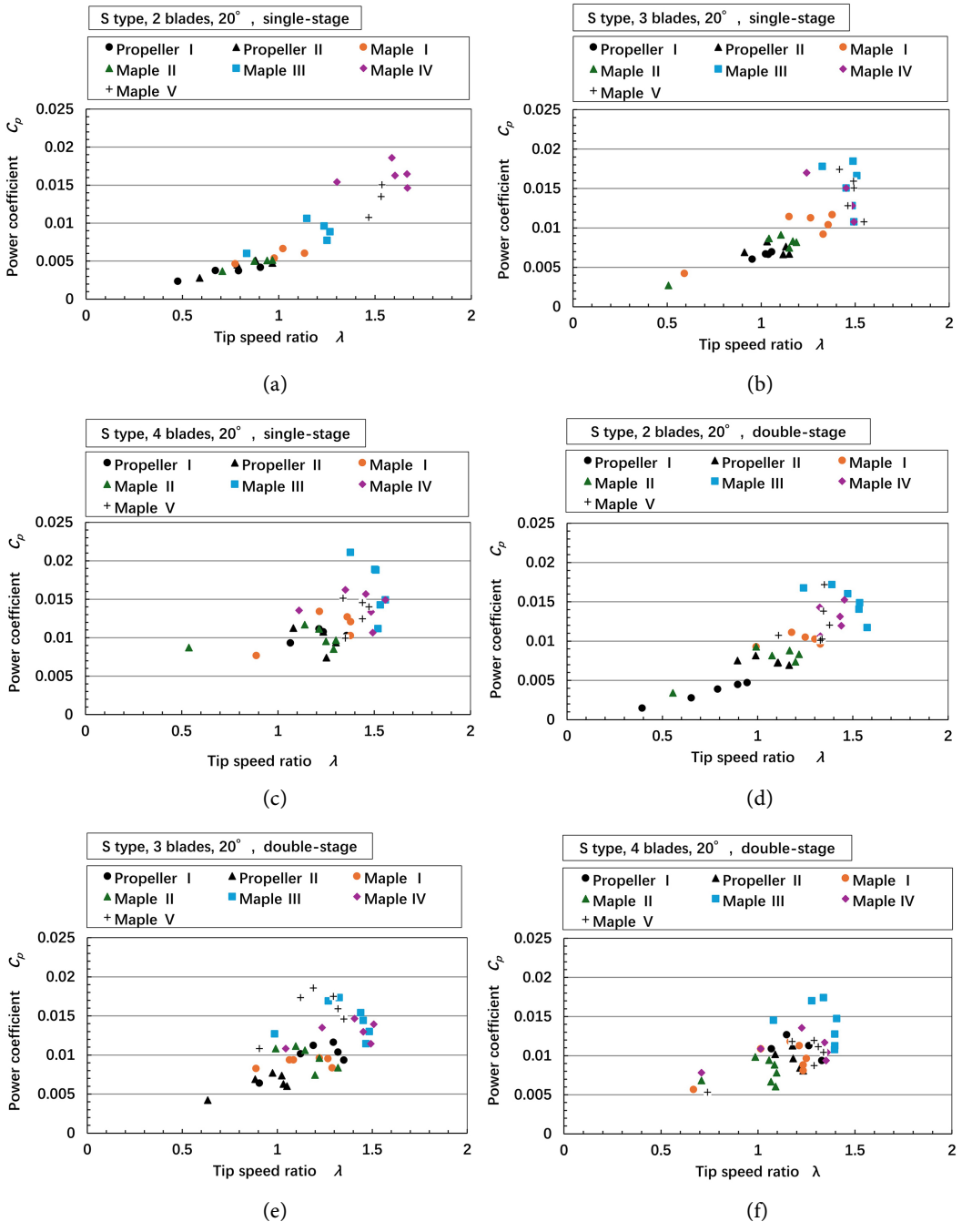


Figure 5. C_p to λ in cases of S-type maple seed blade compared to propeller type in the low wind-speed range: (a), (d) 2 blades; (b), (e) 3 blades; (c), (f) 4 blades; (a)-(c) single stage; (d)-(f) double stage.

In comparison to a current micro wind turbine with 0 - 2 tip-speed ratio λ and

a power coefficient C_p of 0.05 - 0.15 [8], regarding partial conditions, the maple seed-type wind turbine had almost the same C_p and I values, with Figure 4 and Figure 5 suggesting a C_p of less than 0.05 might even be possible. Therefore, the maple seed-type wind turbine using 168-mm rotor diameter could belong in the category less than micro wind turbine, nano wind turbine. This result and optimized performance of the design were related to the wind turbine-inspired dual-mode possessing characteristics of both lift and drag, as was pointed out in our previous study [16].

4. Perspective

The performance of wind turbines in urban and rural areas depends on complex wind conditions, such as turbulence induced by the obstruction of buildings, terrain, etc. Among the critical issues to be settled regarding performance are the length, scale, materials, and shape of the blades, in addition to noise, vibration, fatigue damage, and other safety challenges. These subjects have been the focus of many studies worldwide [9] [18]-[24]. The challenges of installing wind turbines on a small scale have produced findings that allow power generation in homes, schools, and businesses. However, if the scale of the small wind turbine were reduced further to be affordable and available, applications could be spread throughout urban areas. Designing an origami-inspired micro-sized wind turbine with rotor diameters of less than 0.2-m [25] to accommodate limited space availability, prevent noise pollution and environmental hazards, and avoid aesthetic public objections has been a unique challenge.

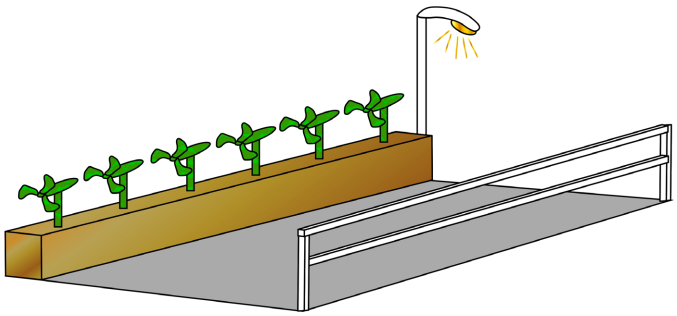


Figure 6. Schematic diagram of possible maple-seed type wind turbine application in urban or rural area.

The micro-scale wind turbine proposed in the present study resolves many of the same issues as the foregoing studies—for example, reducing noise and enhancing blade strength in times of strong wind due to the downstream reclination of flat and slightly bent blades [16]. As the turbine blades in this experiment were not fixed to the wind direction, the turbine could be easily turned to that direction, and the miniaturized scale ensured safe operation. Thus, multiple maple-seed micro wind turbines could be aligned without spoiling the scenery, such as along the roadside as shown in Figure 6, or in the corner of an underground passage in a

subway to power lighting. Installation inside residential buildings could be effective for charging smartphone batteries, which could be vital during, for example, seismic disasters.

5. Conclusion

This study demonstrates the feasibility of installing wind turbines safely and easily in urban and rural areas using a 168-mm rotor diameter (micro) turbine, with slightly bent maple seed-type flat blades that are reclined downstream. The wind turbine features noise reduction and enhanced blade strength, due to the reclination of the blades preventing generation of a vortex around the blade. The findings of the present study indicate that optimization of the performance of the maple-seed blade for C_p to *1* can be summarized by the following key points: C_p to *1* is larger for the L type blade than the S type blade; it is the largest for the 20-degree angle of the attachment; in the case of 2 or 3 blades, single stage is larger than double stage; the maple seed-type is larger than the propeller type. Regarding the blade shape, C_p and *1* were larger in the cases of bent edge, wide width, and diverging edge of the blade than in the cases of straight, narrow, and tapering off blade, regardless of S or L types, number of blades, angle, and stage type. The dual-mode with characteristics of both lift and drag wind turbines make it feasible to produce electric power even at low wind speed. This turbine design ensures optimized performance in urban or rural built-environments protecting aesthetic architectural appearance, and offering reliable and easily available energy toward meeting the UN's SDGs. In addition, the micro-scale and maple seed-type wind turbine proposed in the present study resolves many of issues such as noise created by the rotation and blade strength in times of strong wind realize reducing the noise and enhancing the blade strength so that this wind turbine is suitable for optical performance in urban.

Conflicts of Interest

The author has no conflict of interest to declare.

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