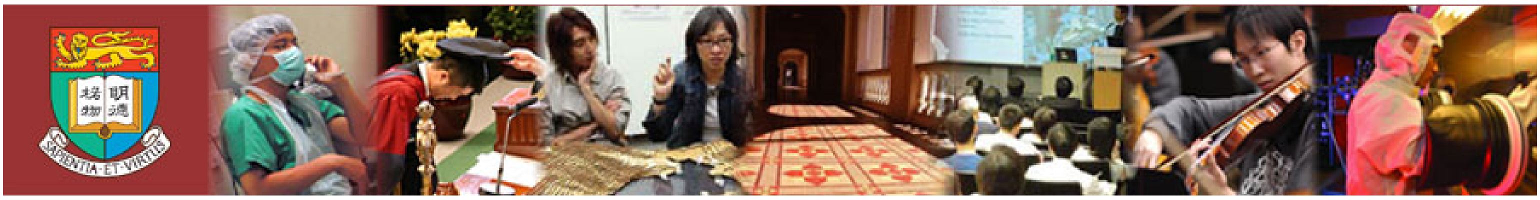

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Author(s)	Leung, YC; Leung, MKH; Gambarota, L; Deng, Y
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5 Micro-wind Turbine System in Urban Environment

Leung, D.Y.C.[1], Leung, M.K.H. [2], Gambarota, L.[3] and Deng, Y.[1]
[1] Department of Mechanical Engineering, the University of Hong Kong, Hong Kong
[2] School of Energy & Environment, City University of Hong Kong, Hong Kong.
Motorwave Group (Holding) Ltd.

Abstract

Wind power is identified to be of great potential for extensive development in many countries to reduce the fossil fuel based power generation. Conventional three blades wind turbines are commonly used in locations with high wind energy density, while small wind turbines are developed for less windy locations such as urban areas and flat lands. An innovative micro wind turbine was developed to generate power in urban environment where wind speed is usually low. Differing from the traditional wind turbine that can be connected directly to the grid, this system is linked to a small generator and batteries, and mainly used for local applications. The advantage of the micro wind turbine is that, apart from its low cost, it can be propelled by a very low wind speed. Computation fluid dynamics (CFD) simulations have been conducted to help evaluate the performance of a single micro wind turbine.

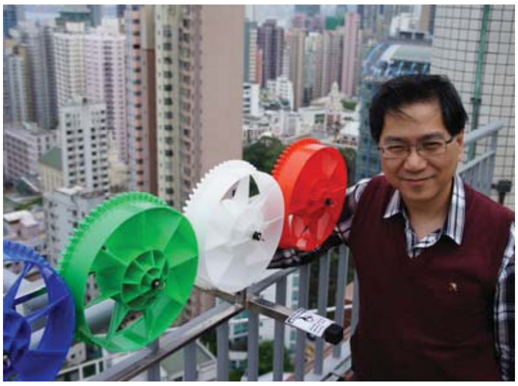

Figure 5-1 Prof. Dennis Leung and the Micro Wind Turbine on a roof in HKU

5.1 Introduction

Global warming and climate change issues boost the development of renewable energy in the world over the past decade. Up to now more than 80 countries have setup targets for their own renewable energy futures, and enacted relevant renewable energy policies in order to reduce their carbon emissions [REN21]. Table 6-1 shows the renewable energy targets adopted by major countries. The figures indicate our great reliance on renewable energy in the next ten to fifteen years.

Among various renewable resources, wind energy is considered to be the most feasible for fast development in many countries in both short and long term, and provides the main driving force for substituting electricity generated from coal-fired power stations. In the ten years from 2001 to 2010, the global wind power installed capacity rose from about 20 GW to 200 GW (Global Wind Energy Council). Over the years, wind energy technology has been developed in many new dimensions, such as aerodynamics, structural mechanics and mechanical engineering. Moreover, it is mainly developed in two directions: large-scale and small-scale [Jureczko et al. 2005]. The main trend of wind turbine development is to implement large-scale wind energy systems in offshore or land based wind farms where the wind energy density is high. The wind turbines used in these systems vary from several hundreds kW to several MW, with rotor diameters from several ten meters to over one hundred meters.

On the other hand, in regions of low wind speed and in crowded urban areas, miniature wind machines or micro wind turbines are more suitable due to the space limitation and low cut-in wind speed (the minimum wind speed for the wind turbines to produce electricity). A small wind turbine, with a rotor diameter as small as one meter or less, can often be set up and stand alone on the roof of houses and buildings. To make it more flexible for usage, this kind of wind energy converter is normally directly linked to batteries or battery systems rather than connected to the electric grid. As its capacity is not big (usually <1kW), its prime cost is not very high and is affordable for many household applications. This small scale wind turbine has received attention in recent years and many research works have been conducted, mainly for optimization of their performance.

Countries	Renewable energy target	Year
EU*	20%	2020
U.S.A.	25%	2025
China	15%	2020
Australia	20%	2020
Russia	4.5%	2020
Japan	1.63%	2014

* Baseline target (may be different for different EU countries) (Data from Wikipedia 2011)

Table 5-1 Renewable energy target for major countries.

Various theoretical methods are available to determine the aerodynamic forces acting on the blades of a horizontal axis wind turbine (HAWT) [Wang et al. 2008], such as the Blade Element Momentum (BEM) theory [Varol et al. 2001, Jureczko et al. 2005, Lanzafame & Messina 2007], Lifting Line Method (LLM) [Duquette & Visser 2003], Lifting Surfaces Method (LSM) (de Bruin 2003), N-body/

particle simulation method, and asymptotic expansion method (Euler special) (van Busse 1995). Among them, the BEM method is the simplest and most commonly used for research purposes. In this paper the performance of a specially-designed low-cost micro wind turbine is evaluated using a computational fluid dynamics (CFD) technique which is verified with physical tests conducted in a wind tunnel. [Deng 2008]

5.2 Design of an innovative micro-wind turbine

The wind turbine under investigation is a drag device based micro wind turbine, as shown in Fig. 5-2 and 5-3. Different from conventional two- or three-blade wind turbines, this micro wind turbine employs a fan-type blade configuration instead of an aerofoil-type. This has a functional advantage of increased power efficiency for micro wind turbine [Hirahara et al. 2005].

The edgewise view defines the blade thickness distribution over the blade length. Many large wind turbines utilize linear taper blades from the root to the tip for rigidity [Habali & Saleh 2000]. Since the blade of the micro wind turbine is not very long, it is designed to be in mono thickness along the blade length. Similar to most wind turbines, twisted blades are used to capture higher torque under different wind conditions.

The twist extent of the turbine blade is clearly displayed in the transaction view. The twist angle of the micro wind turbine is a critical parameter for the present computation and optimization work, and it has a strong relationship with the blade subtend-angle of the micro wind turbine. Important geometric parameters of a typical micro wind turbine are shown in Table 5-2.

Figure 5-2 Micro wind turbine under studying

The advantage of this micro fan-bladed wind turbine design is that a system, consisting of multiple turbines connected together through their external gears, can be easily setup to meet any power demand in a flexible manner (see Section 5.4). Such blade and turbine designs can be produced by injection molding for mass production; therefore the cost of the system is only about one third of conventional wind turbine system designs.

Description	Value
radius of the micro wind turbine	117 mm
radius of the blade tip circle	115 mm
radius of the blade root circle	50 mm
blade subtend-angle (the angle between the two edges of the blade in the front view) (α)	30°
twist angle of the turbine blade (the angle between the chord line of the blade tip and that of the blade root) (β)	21°
width of the blade area (Z)	60 mm
number of blade (N_B)	8
Solidity (Σ) ($\sigma = N_B \times A_s / \pi R^2$)	52.2%

Table 5-2 Geometric parameters of a typical micro wind turbine.

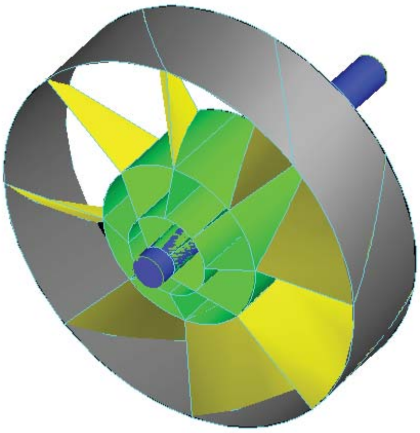

Figure 5-3 Micro wind turbine (CAD design)

5.3 Factors to be considered in the design of a micro-wind turbine

Many factors such as the effect of blade subtend-angle of the turbine and number of turbine blades may affect the power coefficient of the wind turbine. A number of simulations were conducted by the CFD to obtain the followings:

(i) the maximal angular velocity of the micro wind turbine at different wind speeds;

(ii) the torque acting on the micro wind turbine when they are stationary and rotating at a certain angular velocity at different wind speeds;

(iii) the mechanical energy produced by the micro wind turbine at different wind speeds.

For demonstration, a few cases are presented and discussed in this paper. More information can be found in Deng [2008].

5.3.1 Tip speed ratio

Figure 5-3 shows the computed relationship between the power coefficient (Cp) and the tip speed ratio (λ) of the micro wind turbine. It is recognized that small-scale multi-bladed wind turbines normally operate at a tip speed ratio between 0 to 2 while the large-scale one with two or three blades operates at a tip speed ratio higher than 4 [Johnson 1985]. As indicated, the tip speed ratio of the present micro wind turbine with a 30-degree blade subtend-angle is between 0 and 1, which meets closely with the Cp- λ characteristic of the traditional, small, multi-bladed wind turbine. Besides, the maximal power coefficient of the micro wind turbine indicates that the efficiency of the transformation from kinetic wind energy to mechanical energy is only about 12%.

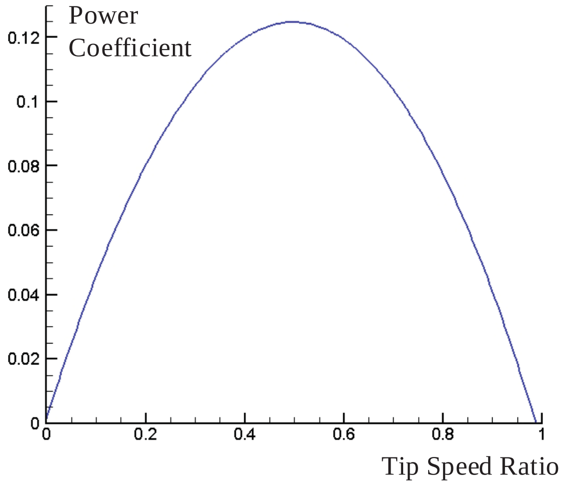

Figure 5-4 Characteristic of the micro wind turbine

5.3.2 Effect of blade subtend-angle

To compare the performance of the micro wind turbine with different blade profiles, they were categorized into several series according to their blade subtend-angle. For each series, the blade number varied from three to a number at which the blade plane of the turbine is covered by the blade projection.

For the blades with 30-degree subtend-angle, the blade number varied from three to twelve. No significant difference in the maximal power output can be observed for the micro wind turbines with eight or more blades as shown in Figure 5-4, while their maximal power outputs are much higher than those turbines with fewer blades. The optimal power coefficient of the turbines with a 30-degree blade subtend-angle is about 12.5% while the optimal tip ratio is 0.5 ~ 0.6 for the 8-bladed to 12-bladed profile. Another important factor indicated in this figure is that the maximal tip speed ratio of the micro wind turbines with different blade numbers is about the same.

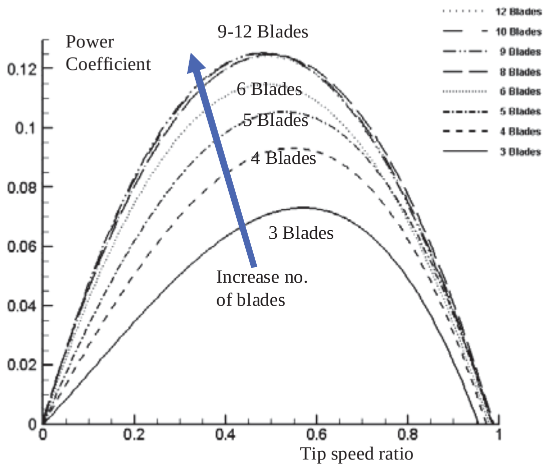

Figure 5-5 Power coefficient with different number of blades with 30-degree blade subtend-angle.

To determine which one of these wind turbine blade designs is optimal, the captured torque for starting the turbine needs to be considered. The larger the torque developed, the easier to overcome the static equilibrium of the turbine. Figure 5-5 shows that there is no obvious difference in the captured torque of the micro wind turbines with eight or more blades. On the other hand, a rotor with fewer blades captures a smaller torque, which is not favourable for energy conversion.

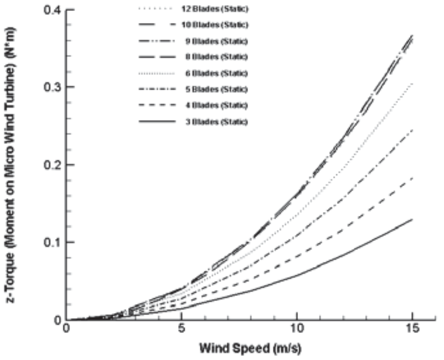

Figure 5-6 Starting effect (torque) with different number of blades
(with 30-degree blade subtend-angle)

The results of other blade subtend-angle can be found elsewhere [Deng 2008]. In general, for a given blade subtend-angle, more blades yields a better performance. However, a fully-occupied rotor plane is not beneficial for both power output and starting effect of micro wind turbine. Moreover, a blade with a subtend-angle larger than 90-degrees is not recommended for micro wind turbine design due to its poor starting performance.

5.3.3 Effect of Solidity

Figure 5-6 shows the relationship between the maximal power coefficient and the solidity of the micro wind turbine. The figure illustrates that the maximal power coefficient of the turbine rises with increase in solidity, and then becomes fairly constant for solidity higher than 0.5. In other words, it is better to select a micro wind turbine profile whose solidity is higher than 0.5 to receive a higher power output.

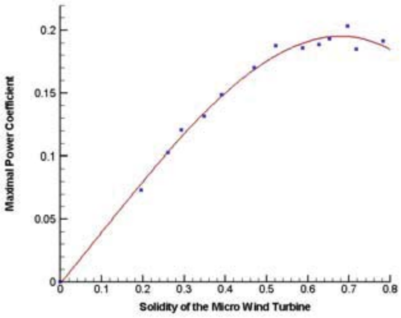

Figure 5-7 Relationship between maximal power coefficients with the solidity

According to the results, the 4-bladed micro wind turbine with 80-degree blade subtend-angle has the highest power coefficient. However, this is not the optimal profile for the micro wind turbine due to its comparatively weak starting torque. Figure 5-7 shows the torque produced by those high-efficiency wind turbine profiles under stationary condition. Among these rotors whose power coefficients are higher than 0.18, the 5-bladed rotor with 60-degree blade subtend-angle is considered to be the optimal micro wind turbine profile. Compared with that of original micro wind turbine profile (30-degree blade subtend-angle, 8-bladed), the maximal power coefficient of the 5-bladed rotor with 60-degree blade subtend-angle raises from 12.5% to 19.3%.

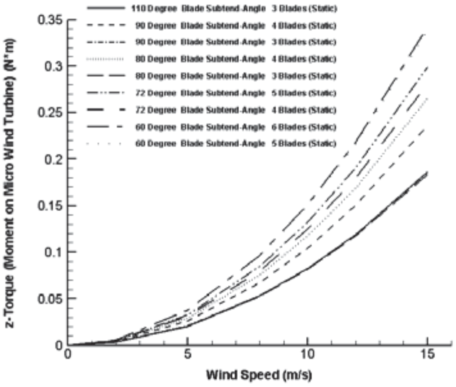

Figure 5-8 Starting effects of several high-power-coefficient micro wind turbines

5.4 Micro-wind turbine system

Section 5.3 describes the performance of a single micro-wind turbine which can develop a finite power even at high wind speed. To increase the power, a number of this micro-wind turbine can be connected together through its external gears so that a larger torque, hence higher power, can be developed (Figure 5-8).

No. of turbines (n)	Increase in power (%)
1	0
2	132
3	275
4	436
5	525

Table 5-3 Increase in power with increasing the number of turbine

Wind speed (m/s)	**Power (W)**
2	0.4
3	1.3
4	3
5	6
6	10
7	17
8	25
9	36
10	50

Table 5-4 Power obtained for a 8-micro-wind-turbine system at various wind speeds.

An experiment has been conducted in the wind tunnel to find the relationship between the power developed and the number of wind turbine connected in a straight line. Table 5-3 shows the increase in power with increasing number of turbine at a wind speed of 6.5 m/s.

As can be observed, the power increases with increasing the number of turbines. However, it was found that the increase is not linear, particularly for the number beyond 5 and there is no power increase for n>10 [Leung 2009]. It is therefore recommended that not more than 10 micro-wind turbines should be connected together serving one generator for maximizing the power generation capability.

Table 5-4 shows the power generated at different wind speeds measured in an environmental wind tunnel. As can be observed, power can be generated at a low wind speed and the magnitude increases quickly at larger wind speeds. Useful power can be obtained if a number of these micro wind turbines can be grouped together for power generation.

Figure 5-9 Wind tunnel test of micro wind turbine system.

5.5 Conclusions

This study investigates the variation of the performance of micro wind turbine with different design parameters using CFD analysis. The results showed that the performances of high-solidity wind rotors are better than those of low-solidity ones. The optimization results show that the preferable solidity of the micro wind turbine is higher than 50%. Through the CFD analysis, it is found that rotors with more blades can produce higher torque when they are stationary. As a result, a multi-blade approach is favorable for a micro scale wind turbine system. The 5-blade micro wind turbine with 60-degree blade subtend-angle is found to be the optimal turbine profile with the consideration of the power coefficient and starting effect. Its maximal power coefficient is much higher than that of the preliminary turbine design (8-bladed rotor with 30-degree blade subtend-angle) and its higher power coefficient range is much wider.

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