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Experimental investigation and performance modeling of centimeter-scale micro-wind turbine energy harvesters

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ABSTRACT

Centimeter-scale micro wind turbines have been proposed to power small devices. Design models and operating conditions for large scale wind turbines do not directly apply towards these small harvesters. We perform an experimental investigation of a swirl-type micro-wind turbine. We measure the useful power extracted from this turbine in an open circuit suction type wind tunnel facility. The optimal resistive loads for different flow speeds are determined. A model for the friction, torque drive and generated power is derived and validated. The effect of varying the direction of incident flow on the turbine performance is also determined. The results show an optimal combination between the rotor diameter and the number of rotor revolutions. The power density and efficiency of this turbine were found to be larger than previously tested turbines that have slightly larger diameters. This is true over a broad range of free stream speeds. Finally, because of its shape, the swirl configuration is effective in harvesting power for yaw angles of $\pm 30°$.

1. Introduction

Power needs to operate sensors pose a major limitation when considering their use for monitoring and control. These needs are augmented when the sensors are in remote locations, their number is large, as in the case of wireless sensing networks, or when complementary components, such as cyber security devices, also need to be powered. These needs have raised the interest in developing technologies to harvest energy from ambient media such as solar power, thermal gradients, mechanical vibrations and air and water flows. Table 1 shows approximate values for the power density that can be released from these sources (Mathúna et al., 2008).

Significant advancements have been made in designing wind turbines over the past thirty years to cover a wide range of applications. Clausen and Wood (1999) classified relatively small size wind turbines into three categories based on their typical use by characterizing the wind turbine diameter (D) and the output power (P): micro (1.5 m; 1 kW) to power electric fences, remote telecommunications, equipment on yachts and the like; mid-range (2.5 m; 5 kW) to power a single remote house; and mini (5 m; 20 kW) to power small grids for remote communities. On the other hand, powering individual sensors requires power levels in the range of 10–100 mW. As such, there has been increasing interest in developing centimeter-scale micro-wind turbines (CSMWT). For example, such turbines can be placed in air conditioning and ventilation ducts, without a major obstruction effect (duct cross-sectional area divided by wind turbine disk area $<0.18\%$), to power micro-wireless sensors, smoke and gas detectors and temperature controllers. At this scale, such turbines need to be carefully designed to operate efficiently at low wind speeds.

Unfortunately, design models and optimal operating conditions proposed for large scale wind turbines do not directly apply towards the design and operation of CSMWT. These turbines have different aerodynamic behavior compared to their large-scale counterparts. The low Reynolds number regime of centimeter-scale micro-wind turbines projects a fundamental shift in flow characteristics and in quantities such as lift and drag coefficients at the small scale from the large-scale wind turbine. The rated speed is an another important parameter in the design of CSMWT. This speed is the incoming flow speed of the wind at which the turbine starts to produce power. It depends on both total inertia and internal friction of the system including the rotor, ball bearings and the generator. The rated speed decreases with decreasing wind turbine size due to lower inertia. However, decreasing the size of wind turbine blades reduces the available aerodynamic torque and, thus, increases the rated speed. These opposing factors should be optimized when designing a centimeter-scale micro-wind turbine with a desired rated speed and output power. As a

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measure of the design quality, the power density (output power per unit area) and the efficiency of a micro-wind turbine should be improved by reducing frictional losses and improving the generator efficiency. This presents another challenge in terms of achieving the desired number of revolutions of the rotor shaft. Therefore, building an effective small size generator with a low starting torque and a high voltage-to-rpm ratio is a critical design criterion. Overcoming these challenges and optimization of the performance of CSMWT requires good estimates of their aerodynamic power, electromechanical coefficients and overall efficiency. In turn, this requires the development of capabilities to model and simulate the output power of small-size wind turbines.

Many investigations have been performed to evaluate the performance of CSMWT. Howey et al. (2011) investigated experimentally and numerically a miniature shrouded ducted type micro-wind turbine with a 2 cm rotor diameter and a 3.2 cm outer diameter. They showed that the fabricated MWT can deliver power levels from 80 μW to 2.5 mW over a wind speed range from 3 m/s to 7 m/s. The overall efficiency of that turbine was less than 2%. Hossain et al. (2007) studied the effects of scaled MWT in single and grid arrangements using PIV, hot-wire and ultrasonic anemometers. Particularly, they investigated the downwash flow pattern for the smaller scale wind turbine ($D = 5$ cm) in an array arrangement. They calculated the wake deficit ratio for the inner region, outer region and intermediate region to control the wake by using a suitable architecture of the micro-wind turbines. However, they did not give power levels associated with the different arrangements. Carli et al. (2010) maximized the efficiency of their micro-wind turbine ($D = 6$ cm) using a buck-boost converter based maximum power point (MPP) circuit with fixed-frequency discontinuous current mode (FF DCM) to emulate a fixed resistance for minimizing the power loss. They were able to increase their conversion efficiency to 87% and the overall efficiency of their turbine to about 5%. Leung et al. (2010) connected fan-bladed micro-wind turbines side by side by using geared meshing to add up the power. They concluded that turbines with high-solidity had higher power coefficients at a specific blade angle. They showed that the five-bladed micro-wind turbine with 60° blade subtended angle yields an optimal power output. Rancourt et al. (2007) examined the effect of the sweep angle on three types of micro-wind turbines. They showed that the efficiency of the wind turbine follows the Schmitz theory, even at small size (4.2 cm diameter). They obtained an efficiency of 9.5% in 11.83 m/s wind speed. They also asserted that at low wind speeds the friction in the generator and electric resistance reduced the energy conversion so the maximum efficiency was only 1.85% and the power provided was 2.4 mW at 5.5 m/s air speed. Table 2 summarizes the operating conditions for previous studies related to CSMWTs.

The above discussion shows that there must be an optimal relation between the rotor type, its diameter, number of blades and flow speed. Developing a model to predict the generated power from CSMWT is important for optimizing its performance. In this work, we test and model the performance of a swirl-type centimeter-scale micro-wind turbine. Particularly, we measure the harvested power at different speeds, electric loads and yaw angles. Then, we present a model for predicting and evaluating the different losses. This model would serve in optimizing the design of centimeter-scale micro-wind turbines. Comparisons of the performance of this turbine with others in terms of efficiency and power density over a broad range of wind speeds are also performed. Tests are also conducted to assess the effects of varying the direction of incident flow on the turbine performance.

Table 1
Energy harvesting sources typical data used for remote wireless environmental sensing.

Power source	Operating condition	Power density	Area or volume
Solar	Outdoors	7500 $\mu W/cm^2$	1 cm^2
Solar	Indoors	100 $\mu W/cm^2$	1 cm^2
Vibration	1 m/s	100 $\mu W/cm^2$	1 cm^3
Thermal	$\Delta T = 5$ °C	60 $\mu W/cm^2$	1 cm^2

2. Experimental setup

2.1. Swirl type CSMWT

The performance of a centimeter-scale micro-wind turbine is based on three major aspects: its geometry, the generator and operating conditions. Various types of CSMWT are shown in Fig. 1.

Table 2
Recent studies and experiments on centimeter-scale MWTs (Maximum performance operating conditions).

Author(s)	***D*** **(cm)**	**Number of blades**	**Air speed** U (m/s)	**Power** P (mW)	**Efficiency** (%)	**Power density** (mW/cm^2)
Howey et al. (2011)	3.2	3–6–12	10	4.3	1.5	1.37
Rancourt et al. (2007)	4.2	3	11.8	130	9.5	9.39
Carli et al. (2010)	6.3	4	4.7	9.97	5.36	0.32
Xu et al. (2013)	7.6	4	10	10	7.6	0.055
Leung et al. (2010)	11.7	8	15	295	1.37	2.74

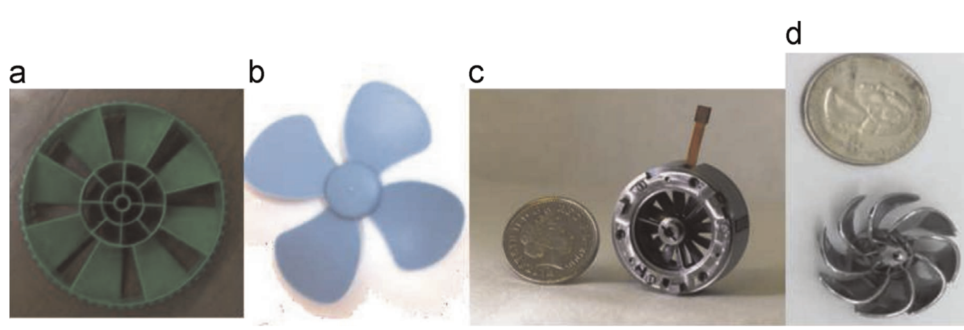

Fig. 1. Various types of centimeter-scale micro-wind turbines. (a) Fan blade with shroud type (Leung et al., 2010), (b) fan type, (c) ducted fan type (Howey et al., 2011) and (d) swirl type used in the present study.