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On the performance of a micro-scale Bach-type turbine as predicted by discrete-vortex simulations

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HIGHLIGHTS

- Flow past a micro Bach-type turbine is solved using a viscous Discrete-Vortex Method.
- Performance of Bach-type turbines is not significantly degraded at small scales.
- In laminar flow, performance of Bach-type turbines can be boosted with wake capture.
- Velocity fluctuation and decreased performance observed for free rotation in water.
- Micro-scale Bach-type turbines can potentially power wireless sensor nodes.

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ABSTRACT

The flow past a Bach-type vertical-axis wind or current turbine is simulated using a viscous Discrete-Vortex Method at a Reynolds number of 1500. The main purpose of the study is to evaluate the suitability of Bach-type turbines for use as micro-scale energy harvesters that can be applied to power, for example, sensor nodes of a wireless sensor network. The maximum power coefficient of the turbine operating at a prescribed constant tip-speed ratio is found to be 0.18, which is comparable to the performance of the same turbine at much higher Reynolds numbers, thus indicating only minimal performance penalty for miniaturization. The speed of the turbine has a strong influence on the evolution of vortical flow structures. A new wake-capturing mechanism that boosts the performance of the turbine is discovered from the simulations for a certain range of tip-speed ratios where the vortex shed by the advancing blade helps drive the returning blade. In addition to prescribed rotation, free rotation of a steel Bach-type turbine in water is also investigated. Significant fluctuation in angular velocity over one period of rotation is observed. This speed fluctuation is found to be detrimental to energy extraction, reducing the maximum power coefficient to approximately 0.16. The estimated power generating capacity of a micro-scale turbine indicates that it can significantly extend the life expectancy of a wireless sensor node or even maintain the node in a low-power state indefinitely.

1. Introduction and background applications

Currently, on-shore utility-scale wind power generation is dominated by horizontal-axis wind turbines (HAWT). Large commercial HAWTs incorporate active orientation (yaw) control [1] and collective or independent blade pitch control [1,2] to ensure the turbine is constantly facing the wind and operating at near-optimal load. As an alternative to HAWTs, vertical-axis wind turbines (VAWT) are also being developed and improved. Although less popular for on-shore applications, VAWTs have a number of advantages over HAWTs. First of all, VAWTs can work with any wind direction, and a yaw-control mechanism is not needed, leading to simpler and cheaper constructions. Further, VAWTs have a smaller footprint and can be arranged in close-packed arrays. In fact, it has been found that it is possible to increase power extraction efficiency of VAWTs through constructive aerodynamic interactions between a pair of counter-rotating VAWTs [3].

VAWTs can be divided into two different types: lift-based Darrieus VAWTs and drag-based Savonius-type [4] or Bach-type [5] VAWTs. Compared to drag-based VAWTs, Darrieus VAWTs operate at a higher tip-speed ratio (λ) and are generally more efficient [6]; thus, Darrieus VAWTs are usually preferred for large-scale wind energy applications. However, Darrieus VAWTs have a low starting torque and are sometimes used in conjunction with a Savonius-type VAWT to improve their self-starting capability [7]. On the

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Nomenclature

Variables

A	rotor cross-sectional area
B_g^*	non-dimensional B_g
C_T	torque coefficient
C_y	vertical force coefficient
d	blade thickness
F_x	horizontal force
I	rotor moment of inertia
k	spring constant
M_{red}	reduced mass
$\mathbf{n}$	unit normal vector
P	turbine power
p^*	non-dimensional relative pressure
R	turbine radius
T	period
T_{dc}	vortex decay time
U_{red}	reduced velocity
u_d, v_d	diffusion velocity
Γ	circulation
δ	nascent vortex blob offset
λ	tip-speed ratio
ρ	fluid density
σ	vortex blob radius
φ	arc section subtended angle
ω	vorticity
B_g	generator damping coefficient
C_P	power coefficient
C_x	horizontal force coefficient
D	turbine diameter, cylinder diameter
f	natural frequency
F_y	vertical force
I^*	non-dimensional I
m	cylinder mass
N	number of vortex blobs
n	time step number
p	relative pressure, half-length of straight section
q	arc section radius
Re	Reynolds number
t	time
U	current speed
u, v	flow velocity
y_c	y-position of cylinder center
γ	vortex sheet strength
θ	rotor angular position
ν	kinematic viscosity
ρ_t	turbine blade density
τ	turbine torque
Ω	angular velocity

Abbreviations

CCW	counterclockwise
DVM	Discrete-Vortex Method
VIV	Vortex-Induced Vibration
CW	clockwise
GPU	Graphics Processing Unit
WSN	wireless sensor network

other hand, drag-based VAWTs operate at a much lower λ and have high starting and operational torque. Darrieus rotors and Savonius/Bach rotors can also be utilized as water current or tidal turbines [8,9].

Although less efficient than their lift-based counterparts, drag-based turbines are believed to be particularly suitable for use as micro-scale power harvesters. In particular, Savonius-type and Bach-type turbines can be used as power sources for wireless sensor networks (WSN) [10]. A WSN may consist of thousands of low-cost sensor nodes spread out in a large geographic area. Each sensor node hosts a suite of Micro-Electro-Mechanical Systems (MEMS) based sensors to monitor temperature, pressure, motion, illumination, etc. A sensor node also contains a microcontroller, wireless transmitters and receivers, data storage, and a power supply, typically a battery. Each node can communicate with each other, forming a network which provides continuous monitoring of a large region. Such a network can be deployed in various terrestrial and marine environments and has a wide range of civil and military applications, from pollution monitoring to motion tracking. Even though the sensor nodes are low-power devices, the usefulness of a battery-powered node is hampered by its finite power supply. Therefore, it is ideal to incorporate an universal micro-scale power harvester in each sensor node. Such a harvester needs to be low-cost, reasonably efficient, and able to operate in an uncontrolled orientation. A drag-based turbine is a potential candidate for this role because of its simple construction, self-starting capability, and insensitivity to the wind or current direction. Finally, a drag-based turbine will need to be able to operate at very low Reynolds numbers because of its small size and low wind or current speeds. For example, a small sensor node placed on the ground will experience very little wind because of the ground boundary layer. To evaluate the potential of drag-based turbines for use as universal micro-scale energy harvesters, computational fluid dynamics is used in this paper to simulate the flow past a Bach-type turbine at a low Reynolds number ($Re = 1500$) and calculate its power extraction efficiency. Detailed numerical investigation on drag-based turbines at this micro scale has not been found in the existing literature. However, several researchers have already started to show interest in small-scale wind turbines [11,12]. In particular, a very recent study investigated experimentally the performances of 3D printed miniature drag-based turbines of a slightly larger scale (Reynolds number based on turbine diameter around 5×10^4) [12]. The miniature turbines were used to power 4 light-emitting diodes, demonstrating the potential for this type of small-scale wind-energy devices.

A sizable number of numerical simulations of flow past drag-based turbines can be found [13]. Typically, these numerical analyses are carried out in the turbulent regime using mesh-based methods and various turbulence models (see e.g., [14–16]). Few studies, however, have been done on the performance of drag-based turbines at smaller scales and low wind or current speeds. In this case, the flow can be modeled as laminar and two dimensional. The viscous Discrete-Vortex Method (DVM) is particularly attractive for solving this type of flow. There have been several previous DVM analyses of drag-based turbines [17–23]. These previous DVM computations were focused on the wake of the turbine and did not directly simulate vorticity diffusion; boundary-layer separation and vortex shedding were limited to the edge of the turbine blade. Computational approaches in a similar spirit have also been used to efficiently predict the blade forces and wake of a lift-based turbine [24–27]. Free vortex filaments released near the blade trailing edge are used to construct the unsteady wake, and a dynamic stall model may be incorporated to accommodate large blade angle of attack [26–28]. In this paper, a fully viscous DVM is used to simulate the flow. Viscosity and the effect of Reynolds number are explicitly accounted for through vorticity diffusion,