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Study of static and dynamic performances of miniature Savonius-type wind energy harvesters

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Abstract

Non-polluting and renewable wind energy harnessed by means of large-scale wind turbines has been well-studied and applied. However, the development of miniature wind energy harvesters is left behind due to little attention and effort. In this work, a miniature air-driven Savonius-type energy harvester is three-dimensionally designed. The energy harvester is 3D printed and experimentally tested. Experimental results prove the energy harvester to be associated with a cut-in Reynolds number of 5.95×10^5 and the maximum overall energy conversion efficiency of 5.16% approximately. To better understand the static and dynamic performances of the designed energy harvester, three-dimensional numerical study is conducted to simulate the experiment. Based on both experimental and numerical results, means to enhance energy harvester's static and dynamic performance are proposed and validated. It is shown that with improved designs, the cut-in Reynolds number can be reduced to 4.33×10^5 and the overall energy conversion efficiency can be increased to approximately 6.59%.

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1. Introduction

Wind energy has become major contributor in global renewable energy industry for its non-polluting and renewable nature that generates electricity with zero fossil fuel cost and toxic waste emission [1]. The global cumulative wind energy installed capacity has reached 432.88 GW, at an average annual growth rate of 119% in the last five years [2]. This is greatly supported by extensive research resources dedicated to explore wind turbine potentialities.

The Savonius turbine attracts much attention for its simple structure, low construction cost and better

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self-starting capability [3]. The power conversion efficiency has been improved greatly by means of optimizing turbine and accessory parts designs, both experimentally and numerically [4,5]. However, few studies have been reported on crossflow Savonius-type wind turbine with axis of rotation perpendicular to oncoming air flow direction but parallel with the ground. This partially motivates the present study to explore this alternative configuration of Savonius-type wind turbine.

Additionally, it is possible to harness from ‘man-made’ wind energy sources, including wind flows associated with complex urban geometry and HVAC (heating, ventilating and air conditioning) exhaust systems [6]. Energy harvesting methods based on various mechanisms are reported [7-9], and wind turbine approach is also explored [10]. It is to be noted that wind turbine size is limited by installation space available. Therefore, another motivation of this study is to investigate wind energy harvester performance at miniature scale.

In this work, a miniature air-driven Savonius-type energy harvester in crossflow configuration is presented. Its static and dynamic performances are studied both experimentally and numerically. Further possible improvements to the designed energy harvester are suggested and experimentally tested.

2. Methods

2.1. Energy harvester design and fabrication

The benchmark energy harvester consists of three half-cylinder blades, end plates at both ends and a connecting solid shaft. An electromagnetic energy convertor is also designed to generate electrical power. When the harvester is rotating, the magnet attached to the shaft will rotate as well. The rotating magnet place within the electromagnetic convertor will induce electromotive force (emf) in the surrounding copper induction coil based on Faraday’s law [11]. The energy harvester model, and its accessory parts (electromagnetic convertor and shaft support) (as shown in Fig. 1a) are designed by using SolidWorks. The harvester model is very small in dimension (100mm×100mm), thus together with accessory parts, are easily fabricated by using a desktop 3D printer, MakerBot Replicator 2.

2.2. Experimental approach

The designed energy harvester performance is evaluated by using AF6407 closed-loop wind tunnel in Nanyang Technological University (Fig. 1b). The model is tested at different Reynolds numbers (Re), which are determined by using a Sentry ST372 IR Thermo-Anemometer. Rotation speed of the harvester is measured by using an Acez Portable Tachometer AI3030. The induced emf is measured and recorded with Tektronix TDS1012 Two Channel Digital Storage Oscilloscope.

2.3. Numerical approach

3D Computational Fluid Dynamics (CFD) numerical study is done by using ANSYS Workbench 16.1. The geometric model and meshing are prepared by using SolidWorks and ANSYS Workbench Meshing package, respectively. The ANSYS CFX-Solver is used to solve the unsteady Reynolds Averaged Navier Stokes equations, with second order of accuracy in time. Based on previous similar studies [12], the turbulence model used is the Shear Stress Transport (SST) model. Two energy harvester models are used for validating numerical results (Fig. 1c), as compared to benchmark model, Model 1 has its end plates removed and Model 2 has its solid central shaft removed. It can be seen that good agreement is achieved between experimental measurements and numerically predicted results.

In static study, the harvester model is fixed stationary with different rotor angles (θ), which are the

angles between the harvester blade and air flow direction. The static torques at various Re are determined.

In dynamic study, the harvester model and its vicinity is set as rotating domain while the rest is stationary. Two domains are coupled via applying the Transient Rotor model. Time step is set to be less than time take for 1° of rotation [13]. The stabilized torque value is recorded after at least five revolutions are completed.

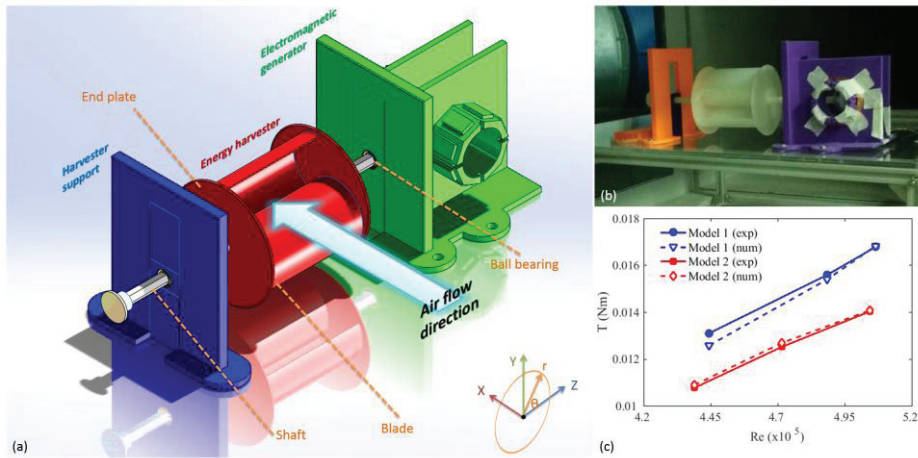


Fig. 1. (a)Schematic diagram and (b) 3D printed model of the designed energy harvesting system. (c) Validation of torque on harvester blades.

3. Results and discussions

3.1. Static performance

Static performance addresses how well the energy harvester can self-start. An energy harvester with better static performance will have lower cut-in Reynolds numbers (Re_c) and is able to self-start rotation at relatively lower Re .

Rotation starts when the torque generated by air flow exceeds the frictional torque between shaft and harvester support. In numerical study, static torque (T_s) is determined every 5° interval in θ . T_s is calculated about rotation axis by summing the cross products of the pressure and viscous forces vectors on blades with the moment vector. Static torque coefficient (C_{Ts}) is used to characterize the likelihood that the energy harvester is to self-start, and it is evaluated as:

$$C_{Ts} = \frac{T_s}{0.5\rho AR(\mu Re/\rho D_h)^2} \tag{1}$$

where ρ is air density, A is the swept area of energy harvester, R is the radius of it, μ is air dynamic viscosity and D_h is the hydraulic diameter of the wind tunnel in meter. It is to be noted that a large positive C_{Ts} value is desirable, but harvester is unlikely to self-start rotation if C_{Ts} is negative or very close to zero.

Changes in C_{Ts} value at different Re can be seen in Fig. 2a. Positive C_{Ts} is observed in ranges of $\theta=0^\circ$ to 20° , 55° to 140° , 175° to 260° , and 295° to 360° . In these ranges, pressure is built up at concave sides of the blades and the energy harvester is more likely to self-start (Fig. 2c). In contrast, high-pressure regions at convex sides of blade produce counter-rotation torque and negative C_{Ts} (Fig. 2b). It is also

noticed that C_{Ts} does not increase with increased Re significantly, and the harvester rotor angle is the dominant factor. Therefore, it can be concluded that the geometric structure and relative position of the energy harvester with oncoming air flow will determine the self-starting capability of it.

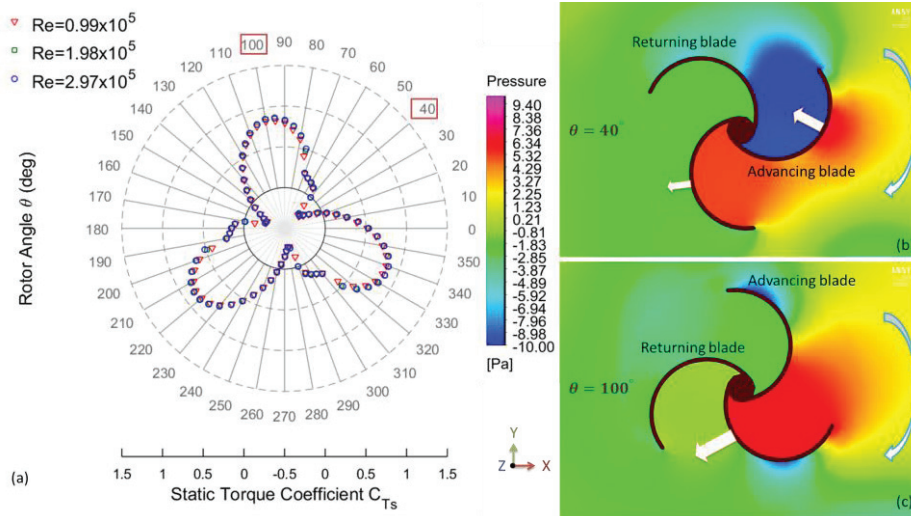


Fig. 2. (a) C_{Ts} at different θ and different Re . Pressure distribution at (b) $\theta=40^\circ$ and (c) $\theta=100^\circ$.

Experimental results confirm the self-starting capability of designed energy harvester and it self-starts rotation at $Re_c=5.95 \times 10^5$. Self-starting capability is further improved by reducing undesirable high pressure at convex sides of blades. It is done by introducing additional air pathways in the energy harvester, such as removing harvester central shafts or end-plates. Experimental results show that Re_c can be reduced to 4.33×10^5 and 4.35×10^5 , respectively.

3.2. Dynamic performance

Dynamic performance concerns how efficient the harvester converts energy. It is characterized by the overall energy conversion efficiency (η), which is the percentage of mechanical (kinetic energy) power available in the moving air that is converted to electrical power. At a given Re , energy harvester that is driven to rotate faster will induce higher emf and electrical power, thus obtain higher η .

In numerical dynamic study, torque values (T) after five revolutions are averaged to evaluate power coefficient (C_P) at different tip speed ratios (λ). The C_P can be obtained with

$$C_P = \frac{P}{0.5\rho AR(\mu Re/\rho D_h)^3} = \frac{T}{0.5\rho AR(\mu Re/\rho D_h)^2} \frac{\omega R}{(\mu Re/\rho D_h)} = C_{Td}\lambda \quad (2)$$

where P is power produced by energy harvester, and $\lambda = \omega R / (\mu Re / \rho D_h)$ with ω as the rotation speed of energy harvester. The dynamic torque coefficient (C_{Td}) can be determined by:

$$C_{Td} = \frac{T}{0.5\rho AR(\mu Re/\rho D_h)^2} \quad (3)$$

The characteristic curve of the energy harvester is obtained by evaluating C_P at different values of λ (by varying ω at a given Re). The characteristic curve at $Re=1.49 \times 10^5$ is shown in Fig. 3a. It can be seen

that the highest possible $C_{Pmax}=0.288$.

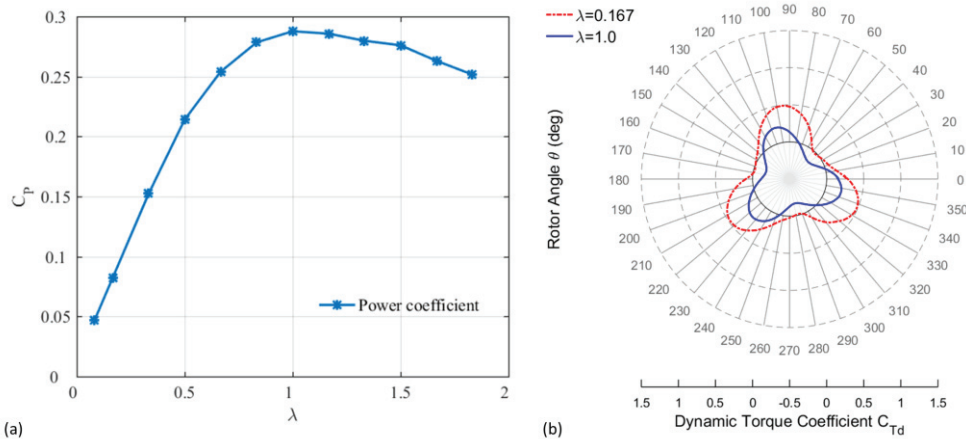


Fig. 3. (a) Characteristic curve of energy harvester and (b) instantaneous C_{Td} at $Re=1.49 \times 10^5$ when the highest possible C_P is achieved at $\lambda=1.0$ and the ω is set to be the same in experiments at $\lambda=0.167$.

Torque within one revolution is also studied, and it is not uniform as shown in Fig. 3b. It can be seen that theoretical C_{Pmax} at $\lambda=1.0$ cannot be practically realized due to ranges of negative C_{Td} . When λ is lowered to 0.167, instantaneous C_{Td} is all positive at every θ . This $\lambda=0.167$ corresponds to the rotation speed that the energy harvester can achieve at $Re=1.49 \times 10^5$ experimentally.

In wind tunnel tests, the designed energy harvester achieves the highest $\eta=5.16\%$ approximately. It is noticed that η is largely affected by how well the pressure is concentrated at the concave sides of the blades. For instance, removal of central shaft or end plates will reduce η to 1.20% and 0.67%, respectively, as pressure is less satisfactorily focused. This understanding suggests the possible way to improve η by taking the interaction between energy harvester and its installation site into consideration. The present model is installed with its concave side facing oncoming air flow at the lower half of the harvester. If the energy harvester with reversed orientation is installed at the edge of a step height, the upward air flow from the near can be utilized as well. Experimental results confirm that this change in installation orientation will increase η to 6.59%, but Re_c remains at a relatively high value of 8.32×10^5 .

4. Conclusions

Miniature Savonius-type energy harvester driven by air crossflow are studied by experimentally and numerically. Experimental results are obtained with wind tunnel in Nanyang Technological University. Experimental results show the initial energy harvester design is associated with a cut-in Reynolds number of $Re_c=5.95 \times 10^5$ and the maximum overall energy conversion efficiency of $\eta=5.16\%$ approximately. To simulate the experiment and to gain insights on the static and dynamic performance of the energy harvester, 3D numerical studies are performed. It is numerically shown that:

- Static performance is dominantly determined by the geometric structure of such energy harvester and its relative position with oncoming air flow.
- Increasing Re has less significant effect on improving static performance.
- Dynamic performance is influenced by how well the pressure can be focused near the concave side of the blades.
- Positive C_{Td} throughout the whole revolution is necessary for the energy harvester to be functioning

practically.

With better understanding of the static or dynamic performances of the energy harvester, improved design is suggested and further tested. Removing central shaft can decrease the cut-in Reynolds number Re_c to 4.33×10^5 . Reversing harvester setting orientation and installing it near the edge of a step height can increase its overall energy conversion efficiency η to 6.59% in comparison with 5.16% of initial design. However, an optimum design achieving both excellent static and dynamic performances is not achieved yet. Future research is needed.

Acknowledgements

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Biography

Ms. Nuomin Han is currently pursuing PhD degree under supervision of As. Prof. Dan Zhao in the School of Mechanical and Aerospace Engineering, College of Engineering, Nanyang Technological University (NTU), Singapore. Before joining NTU, she obtained her Bachelor degree from National University of Singapore in 2014. Her research interests include renewable energy, energy conversion and energy harvesting technologies.