Flow characteristics and operation performance of the drag-type hydrokinetic rotor: a systematic review

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Abstract. The hydrokinetic rotor serves as a critical component in the system of hydropower utilization. Advantages of the drag-type rotor have been recognized while the disadvantages of low efficiency are appreciable. To improve the performance of the drag-type rotor, studies have been performed from multiple aspects. The present study summarized recent achievements of this rotor branch. Particular, emphasis was placed on the relation between flow characteristics and operation performance of the rotor. A systematic description of the recent achievements and methods pertinent to the drag-type rotor is expected to motivate more fruitful work, thereby extending the application of such a promising rotor.

1. Introduction

The utilization of renewable energy has been prioritized worldwide, particularly in recent years. People have suffered from overconsumption of fossil fuels and consequent environmental pollution. This encourages two branches of efforts; one is devoted to the exploration of new energy resources and the other to enhance the efficiency of current energy transformation. Hydro-energy is abundant and clean. Successful utilization of hydro-energy has been substantiated as the potential energy of water is absorbed by hydraulic turbines. Meanwhile, the kinetic energy of water is enormous in rivers and tides. The turbine employed under these conditions are termed hydrokinetic turbine, which differs explicitly from conventional hydraulic turbines. The rotor is the most important component of the hydrokinetic turbine. It interacts directly with flowing water and hence transforms the kinetic energy into mechanical energy. Generally, the hydrokinetic turbine rotors can be divided into two types, namely lift-type rotor and drag-type rotor. The lift-type rotor may achieve high operation efficiency and its applications are more common. In comparison, the knowledge of the drag-type rotor is far from adequate.

The drag-type rotor, represented by the Savonius rotor, initially operated as a wind turbine rotor. The rationale enables it to absorb the kinetic energy of flowing water. The kinetic energy of water is stable, predictable, and has high power density. A comparison between the hydrokinetic and wind turbines performed experimentally and numerically by Sarma N K et al. proves that the performance of the former is better [1]. Moreover, the drag-type hydrokinetic rotor is featured by large startup torque and low rotational speed, which incur less adverse effect on aquatic animals. Furthermore, the drag-type hydrokinetic rotor can adapt to ocean currents, river flows, even flows in manmade channels.

Nearly one hundred years has passed since the invention of Savonius turbine rotor. A diversity of studies on the drag-type rotor has been reported and the obtained conclusions cover theories, design
and tests. However, the overall application of the drag-type rotor is rather limited in engineering fields, particularly those related to water instead of air. The present study aims to systematically analyze recent studies on the drag-type hydrokinetic rotor. All the results presented here have been validated. Major issues that significantly influence the rotor performance are emphasized. It is further expected to provide a reference for subsequent work.

2. Evolution of the drag-type turbine rotor

The conventional Savonius rotor is characterized by an S-shaped cross section. This profile is simple but enables the generation of driving force for the rotor to rotate. Some argued that the cross-sectional profile incurs energy loss and thereby impairs the effective power output. The rotor geometry has been improved based on the conventional shape. The Bach-type rotor shown in Figure 1(a) proves to be a successful innovation as the middle part of the cross-sectional profile is straightened.

Apart from the cross-sectional profile, more geometric parameters such as the aspect ratio, the ratio of rotor height to diameter, and the overlap ratio, the ratio of gap distance to rotor diameter, have been optimized. The participation of endplates helps to reduce the leakage of flow energy. As seen in Figure 1(b), helical blades enable the rotor to adapt to flows from any direction and reduce torque ripple but the torque performance is degraded. Moreover, accessory devices are deployed to increase the performance of the rotor. A ducted nozzle was proposed in [2] and then installed around the rotor, and the efficiency increase was demonstrated. Upstream of the rotor, two plates were used to avoid the adverse impact on the returning blade and concentrate the upstream flow, as indicated in Figure 1(c) [3]. Similar strategies were attempted in [4] and [5]. It is noteworthy that the participation of these accessory devices complicates the whole system and might undermine the stability of the system [6]. Although abundant literature is related to the optimization based on the conventional Savonius rotor, few conclusions are generalizable, which is ascribed to insufficient understanding of the interrelation between the geometric parameters.

Multiple rotors work more efficiently than a single rotor does, as shown in Figure 1(d). The complexity of seeking an optimum configuration of the rotors is high [7]. Not just the inter-rotor distance, but also the relative orientation between neighboring rotors, should be deliberately devised. Essentially, the influence of the wake of the upstream rotor on the downstream rotor has not been elucidated, hindering the advancement of the multi-rotor scheme [8].

![Figure 1](image)

**Figure 1.** Evolution of the drag-type rotor: (a) Bach-type rotor, (b) Helical-bladed rotor, (c) Rotor with accessory plates, (d) Multi-rotor scheme.

3. Methodologies for studies on the drag-type rotor

Although the drag-type rotor is simple in geometry, the principles governing the energy transformation during its operation and guiding the rotor design have not been constructed. Thus far, general theories such as the one-dimensional actuator disc flow theory and blade element momentum (BEM) theory are popular but they were not specifically invented for the drag-type rotor. A hydrodynamic theory was developed to predict the performance of Savonius turbine, the feasibility was found to be susceptible to design parameters and operating conditions [9]. Assumptions are common for the theoretical
models that have been reported and might lower the accuracy of the predicted results. The breakthrough in theoretical aspect is of significance for the development of the rotor.

Various experiments have been performed with respect to the drag-type rotor. On the whole, model experiments are predominant and the circulation loop has been used widely. Inevitably, the model experiments are subject to the influence of primary factors such as the blockage ratio of the test section, the turbulence intensity of the upstream flow, accuracy of the instrument. Eventually, a similarity conversion has to be performed between the data obtained from the model and the performance of the prototype. There are some advices for the experimental preparation; however, each laboratory has its own characteristics and one cannot anticipate all laboratories employ the same experimental rig.

Regarding the experimental study of the drag-type rotor, two aspects have been intensively emphasized. One is the operation performance and the other is the near-rotor flow [10,11]. Essentially, the relation between flow characteristics and performance of the drag-type rotor is of significance for the improvement of the rotor. A comprehensive application of experimental techniques of flow and rotor performance measurement is greatly expected. A typical experimental system for accomplishing such a purpose is schematically shown in Figure 2. An electromagnetic brake is used to impose external loads to the rotor and the rotational speed of the rotor can thereby be regulated. A torquemeter and a tachometer are used to measure both the hydrodynamic moment on the rotor and the rotational speed of the rotor, respectively. Meanwhile, a time-resolved particle image velocimetry (TR-PIV) system is used to non-intrusively measure velocity distributions near the rotor.

![Figure 2. Layout of the experimental system for drag-type rotor.](image)

Another useful tool for investigating the drag-type rotor is the computational fluid dynamics (CFD) technique. Since the flow velocity faced by the hydrokinetic rotor is quite low, the numerical preparation is simplified compared to the treatment of other engineering turbulent flows. The most remarkable advantage of CFD is reflected in the acceleration of the optimization of the rotor. Provided that several geometric parameters are to be considered, there might be dozens of rotor schemes. In this case, experiments are apparently impractical. CFD can be used in this case and the numerical results associated with different rotor schemes can be compared conveniently and comprehensively. Two steps are necessary for obtaining reliable numerical results. One is the grid independence examination and the other is the physical validity examination. The importance of grid can never be overemphasized. Meanwhile, the physical validity should be proved through the comparison between numerical and experimental results.

Various commercial CFD codes are available for numerical simulation of flows around the drag-type rotor. Moreover, some in-house codes play an equivalently important role and they sometimes are more flexible than commercial ones. Some new strategies such as the discrete vortex method have been attempted in the simulation of the wake flow downstream of a Bach-type rotor [12]. Currently, numerical simulation serves as a dominant research method for the drag-type rotor. However, there are some practical factors such as friction and non-uniform upstream flow that cannot be modeled numerically. The deviation between numerical and experimental results is unavoidable.
4. Relation between torque output and near-rotor flow
The static torque on the drag-type rotor is closely related to the relative orientation between the rotor and the upstream flow. Generally, the static torque is used to evaluate the self-startup capability of the rotor. In previous studies, the experimental results obtained as the rotor is in static state have usually been used to examine the validity of the numerical schemes.

The variation of the static torque coefficient with the azimuthal angle of a drag-type rotor, $\theta$, is plotted in Figure 3. Regarding the rotor investigated here, there is a gap between the two rotor blades. The periodicity of the variation of the static torque coefficient is identifiable since the rotor is equipped with two identical blades. The static torque coefficient fluctuates drastically as the azimuthal angle alters, implying complex interaction between the rotor and the incident flow. The rotor considered is advantageous in that negative static torque coefficient is absent. This helps to promote the startup capability of the rotor.

![Figure 3](image)

**Figure 3.** Variation of static torque coefficient with azimuthal angle.

To further explain the variation of the rotor performance with the azimuthal angle, flow patterns near the rotor fixed at three azimuthal angles are shown in Figure 4. As shown in Figure 3, $\theta=40^\circ$ corresponds to the maximum static torque coefficient. Correspondingly, in Figure 4(a), as water passes over the rotor, two vortices are respectively trapped at the concave sides of the two blades. There is no clear wake region downstream of the rotor, which is attributed to the existence of the inter-blade gap. The pressure distributions over the two blades contribute to the production of torque on the rotor. The minimum static torque coefficient arises at $\theta=100^\circ$. In Figure 4(b), relatively high pressure at the upstream side of the returning blade yields negative torque, which counteracts the positive torque on the advancing blade. A saliently large wake is seen immediately downstream of the rotor. As the rotor is fixed at $\theta=160^\circ$, the projection area of the rotor in the streamwise direction is small, the torque generation owing to the pressure difference between the two sides of the downstream blade is large, as indicated in Figure 4(c).

![Figure 4](image)

**Figure 4.** Velocity and pressure distributions near the rotor fixed at three azimuthal angles.
The performance of the drag-type rotor involves not just the torque coefficient but also the power coefficient. For a Bach-type rotor, variations of the two parameters with the tip speed ratio (TSR) are shown in Figure 5. Overall, the torque coefficient varies inversely with TSR, while there is a maximum power coefficient of about 0.27, which is reached at TSR=0.75. For the value of TSR at which the maximum power coefficient arises, rather discrete results have been reported. It is susceptible to the rotor structure and geometric parameters. Traditional knowledge in this aspect is related solely to the wind rotor. For the hydrokinetic rotor, the optimal TSR is larger than expected.

![Figure 5. Variations of torque and power coefficients with tip speed ratio.](image)

5. Startup performance
The startup performance is vital for the drag-type hydrokinetic rotor, which has been widely acknowledged to show large static torque [13]. The startup performance is generally evaluated via the static torque coefficient. However, the static torque coefficient cannot reflect transient phenomena during the startup process. To illustrate the characteristics of the startup process, the rotational speed and torque coefficient during startup process are plotted in Figure 6 as a function of the rotation time. It is seen that the rotor rotates from rest and accelerates to a high rotational speed in a very short span of rotation time. After an unstable transition stage, the rotational speed manifests regular periodic fluctuations.

It is evidenced that the torque varies intensely during the startup process. Nevertheless, the correspondence between the torque coefficient and the angular velocity is not explicit in Figure 6, which demonstrates the imparity between static and dynamics states. To explain the mechanism, flow patterns should be considered, which can be obtained numerically. Additionally, the startup performance of the hydrokinetic rotor is better than that of the wind rotor.

![Figure 6. Time-dependent angular velocity and torque coefficient during startup process.](image)
6. Dynamic performance
To investigate the dynamic performance of the rotor, two methods of specifying the rotation of the rotor have been applied, namely predefined rotation and free rotation. With predefined rotation, the rotor rotates with a constant angular velocity. This method facilitates a constant tip speed ratio and has been commonly used in both experimental and numerical studies. However, in physical reality, the rotational speed of the rotor is largely dependent of the incident flow and the load characteristics; meanwhile, the rotational speed is bound to change with the relative orientation between the rotor and the flow [14]. The other method employs the principle of free rotation, which means that the rotational speed of the rotor is time-dependent. The implementation of the free rotation can be accomplished through solving the motion equations of the rotor.

The torque output performance of the drag-type rotor declines due to fluctuations of the angular velocity. A comparison of the torque coefficient obtained under the conditions of predefined rotation and free rotation is illustrated in Figure 7. It is seen that the phase angle associated with the predefined rotation lags about 45° behind its counterpart. Moreover, the torque coefficient is overestimated as the predefined rotation is adopted.

Heretofore, flow visualization as the rotor rotates has rarely been reported. As the rotor rotates, the synchronization between the image shooting and the rotation of the rotor must be ensured through a shaft encoder. Meanwhile, since the monitored area is limited, the size of the tested rotor should not be too large. Whether the rotor should be made transparent or not has to be considered as well. Provided that the rotor is made of plexiglass, high intensity of the incident light is definitely necessary and the non-uniform light reflection over the curved blade surface should be properly treated.

![Figure 7. Comparison of torque coefficient under different rotation settings.](image)

7. Effect of Reynolds number of upstream flow
Characteristics of the upstream flow influence significantly the flow patterns near the drag-type rotor. Reynolds number serves a most fundamental property of the upstream flow. Variations of the power coefficient of two drag-type rotors with Reynolds number of the upstream flow are shown in Figure 8. It is evidenced that the power coefficient increases with Reynolds number, as is shared by the two rotors. The power output of the conventional Savonius rotor is superior to that of the helical-bladed rotor. Additionally, as Reynolds number of the upstream flow increases, the turbulence intensity might increase accordingly, which boosts the startup performance of the rotor. The reason lies in the disturbance nurtured in highly turbulent flow forces the rotor to oscillate; even with a small increment of azimuthal angle, the rotation of the rotor can be launched. Thus far, the study on the effects of upstream flow conditions on flow characteristics or the performance of the rotor has seldom been reported [15]. In practical applications, various upstream flow conditions have been encountered and some are considerably intricate. For instance, the wave-pattern upstream flow and the shear upstream flow are frequently faced by the hydrokinetic rotor [16]. In laboratories or through CFD, simulation of those upstream flow conditions is not an easy task.
8. Conclusions

Studies on the lift-type rotor have been extensively performed. Flow characteristics and the operation performance of the lift-type rotor have been paid much attention. In comparison, relatively few studies have been devoted to the drag-type rotor used to harness the water energy. The present study summarizes recent work in the drag-type hydrokinetic rotor with validated results. The improvement of the performance of the rotor through geometric and structural optimization is analyzed. The relation between flow characteristics and the torque coefficient of the rotor is explained. Further topics such as the startup performance and upstream flow condition are discussed, providing a comprehensive reference for related work.

Although progression has been continuously made for the drag-type rotor, there is still a large gap between academically obtained conclusions and practical applications. The knowledge of the following three aspects is inadequate. First, although the experimental results are generally deemed more reliable than numerical ones, the experimental setup needs to be standardized. Second, the relation between the near-rotor flow and the performance of the rotor should be inspected at the dynamic state. The last but not least, until now, efforts have not been devoted to the structural stability of the rotor. This is particularly important for the rotor operating in water. Furthermore, the structural property is closely related to the determination of the geometric parameters of the rotor, which influence significantly the operation performance of the rotor.

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