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Experimental investigation of the energy extraction by a fully-passive flapping-foil hydrokinetic turbine prototype

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ABSTRACT

Experiments were conducted to assess the performance of a fully-passive flapping-foil hydrokinetic turbine for which the self-induced and self-sustained blade motions are resulting from the interaction between the blade's elastic supports (springs and dampers) and the flow field. Previous numerical studies have shown that such a turbine can extract a substantial amount of energy from the flow while offering the possibility to simplify the complex mechanical apparatus generally needed to constrain and couple the blade pitching and heaving motions in the case of the conventional fully-constrained flapping-foil turbine. Based on these promising numerical investigations, a prototype was designed and tested in a water channel at a chord Reynolds number of 21000. Robust and periodic motions of large amplitudes were observed leading to an energy harvesting efficiency reaching 31% and a power coefficient of 0.86. The sensitivity of the turbine dynamics to seven different structural and inflow parameters was evaluated experimentally around a baseline case achieving a high level of performance. It was found that the turbine maintains a good performance over a large range of parameters.

1. Introduction

The flapping-foil turbine concept is one of the various innovative and promising sources of clean and renewable energy that have received an increased attention during the last decade (Young et al., 2014; Xiao and Zhu, 2014). It consists in one or multiple blades undergoing both pitching (rotational) and heaving (translational) motions with a swept area that is perpendicular to the flow. Although it would also be possible for these turbines to extract energy from the wind, they have mostly been developed as hydrokinetic turbines, which extract energy from rivers or tidal currents. The flapping-foil turbine concept has proven to be competitive with the horizontal-axis and vertical-axis turbine technologies, with efficiencies exceeding 40% (Kinsey et al., 2011; Kinsey and Dumas, 2012, 2014; Young et al., 2014; Xiao and Zhu, 2014).

In order to reach such a good level of performance, the designers have, in the past, mechanically coupled and constrained the two motions through complex mechanisms, hence making the turbine a single-degree-of-freedom (1-DOF) device (McKinney and DeLaurier, 1981; Kinsey et al., 2011; Xu et al., 2017). This approach allows prescribing the amplitudes and the frequencies of the heaving and pitching motions as well as the phase lag between them. However, several issues can arise from this complexity. First, a significant amount of energy can be lost before being converted into electricity. For example, Kinsey et al. (2011) reported that 25% of the power extracted from the flow by their fully-constrained flapping-foil turbine was lost before reaching the electric generator due to the friction between the different moving components forming

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the coupling mechanism. Moreover, complex mechanical assemblies are usually prone to a higher risk of failure in addition to being more expensive.

Instead of optimizing the coupling mechanism, a more fundamental change has been proposed: the mechanism can simply be removed! One possible way to achieve this is to use an independent actuator for the pitching motion (Kim et al., 2017), making the concept a two-degree-of-freedom (2-DOF) turbine. Let us recall here that efficient flapping-foil turbines usually require only a small amount of energy to drive the pitching motion on a cycle-averaged basis, while the heaving motion accounts for the net energy extraction (Kinsey and Dumas, 2008, 2014; Zhu, 2011). Such a 2-DOF turbine does not necessitate rigid mechanical links to couple the heaving and the pitching motions, but needs a dedicated actuator for the pitching motion, controllers for both degrees of freedom and an electric generator connected to the heaving motion. Moreover, the electric generator of such a turbine may need to act as an actuator at some instants during the turbine blade cycle in order to prescribe the desired heaving motion. Therefore, this motion-constrained strategy still results in a relatively complex apparatus.

Several authors proposed a simplification to the aforementioned 2-DOF version of the flapping-foil turbine by considering a free or passive heaving motion (Abiru and Yoshitake, 2011, 2012; Deng et al., 2015; Derakhshandeh et al., 2016; Griffith et al., 2016; Huxham et al., 2012; Shimizu et al., 2008; Sitorus et al., 2015; Teng et al., 2016; Wu et al., 2014, 2015; Zhan et al., 2017; Zhu et al., 2009; Zhu and Peng, 2009). More specifically, this scenario involves a blade that is elastically supported in heave instead of being connected to the turbine structure with rigid links. One consequence of this simplification is that the heaving motion cannot be prescribed, but rather solely relies on the interaction between the elastically-supported foil and the flow. The heaving motion is thus self-induced and self-sustained. Two-dimensional (2D) numerical studies (Deng et al., 2015; Teng et al., 2016) and experimental works (Abiru and Yoshitake, 2011, 2012; Huxham et al., 2012) reported efficiencies exceeding 30% and 20%, respectively. This "semi-passive" turbine concept does not need a controller in heave and a simpler form of energy-extracting device (generator) can be used. Indeed, since the heaving motion is free, the energy-conversion device never has to act as an actuator. It corresponds in this case to an energy sink throughout the turbine blade cycle. This device could still be an electric generator in order to convert the energy extracted from the flow into electricity, but other possibilities also arise, such as using the flapping-foil turbine concept as a reciprocating pump (Farthing, 2013). However, both an actuator and a controller are still needed to prescribe the pitching motion.

A further simplification, for which both degrees of freedom are decoupled and elastically supported, was first proposed by Peng and Zhu (2009). This is referred to as a fully-passive flapping-foil turbine. For a given flow, they observed four different types of responses depending on the structural parameters characterizing the elastically-supported foil. Among them, only one was suitable for a stable and efficient energy extraction. This response was characterized by periodic pitching and heaving motions with large amplitudes and it led to an efficiency of 20% and a power coefficient of about 0.3. The other responses were either irregular, thereby negatively affecting the predictability and the controllability of the energy extraction, or the foil remained stationary at its equilibrium position and did not extract any energy from the flow. Zhu (2012) demonstrated that the presence of shear in the inflow could lead to new undesired types of responses and, more importantly, could restrict the parameter range for which useful large-amplitude periodic motions are observed. Wang et al. (2017) later found that this parameter range is also affected by the pitch axis location and that a pitch axis located at 0.35 chord length from the leading edge was optimal in their case.

The above-cited studies performed by Peng and Zhu (2009), Zhu (2012) and Wang et al. (2017) have all been conducted in the laminar regime ($Re = 1000$ and $Re = 400$). Veilleux and Dumas (2017) carried out 2D numerical simulations at a much larger Reynolds number of 500 000 using the Spalart–Allmaras URANS turbulence model (Spalart and Allmaras, 1994), which is more representative of the operation of full-scale turbines. As in the works of Peng and Zhu (2009) and Zhu (2012), Veilleux and Dumas (2017) observed different responses of the foil, including large-amplitude periodic motions. Following an optimization process, they obtained a turbine efficiency reaching 29.1% and a power coefficient of 0.935. Furthermore, they pointed out that an adequate synchronization between the pitching and heaving motions is crucial for an optimal energy extraction by fully-passive flapping-foil turbines, as is also the case for their fully-constrained counterparts (Xiao and Zhu, 2014; Young et al., 2014).

While the aforementioned studies reported good results from 2D numerical simulations, the same level of performance has yet to be observed experimentally with a fully-passive flapping-foil turbine prototype. Similar devices have been studied previously but these works did not focus on the energy extraction performance (Amandolese et al., 2013; Pigolotti et al., 2017). Such a prototype has therefore been designed for the present work and has been tested in a water channel with the objective of proving the feasibility and confirming the potential of the fully-passive flapping-foil turbine concept. The current study also evaluates the sensitivity of the turbine performance to the variation of several governing parameters. The fully-passive concept, the experimental setup and the measurement methodology are described in Section 2, while the analysis of a baseline case and the results of a parametric study are presented in Section 3.

2. Methodology

2.1. The fully-passive flapping-foil turbine concept

The fully-passive flapping-foil turbine concept considered in this study is similar to the one described in the work of Veilleux and Dumas (2017). As shown in Fig. 1, it consists in a rigid blade elastically supported by springs in heave and