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Numerical optimization of a fully-passive flapping-airfoil turbine

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A B S T R A C T

This paper deals with an aeroelastic problem that consists into self-sustained, pitch-heave oscillations of an elastically-mounted airfoil. Such oscillations of an airfoil could be used in order to develop a novel, fully-passive hydrokinetic energy flow harvester that is relatively simple from a mechanical point of view. Indeed, the motion of such an airfoil emerges as a result of the fluid-structure interaction between the flow, the airfoil and its elastic supports, and is sustained through a net transfer of energy from the flow to the structure. In this numerical study, the *OpenFOAM-2.1.x* CFD toolbox is used for solving the aeroelastic problem. Through unsteady two-dimensional viscous simulations at a Reynolds number of 500,000, the fully-passive turbine is optimized and investigated to develop a better understanding of the physics at play. Following a gradient-like optimization of the turbine, two-dimensional efficiencies as high as 34% have been obtained, and two fundamental mechanisms have been found to be very beneficial for enhancing the performances of the turbine: the adequate synchronization between both degrees-of-freedom, and the nonsinusoidal shape of the pitching motion.

1. Introduction

The fluid-structure interaction of an airfoil with its surrounding fluid is of great interest in the design process of several devices and structures. It is well known that flutter is the result of a positive net exchange of energy from the fluid to the structure due to negative aerodynamic damping. Sometimes, one is not interested in having an accurate prediction of the total energy transferred to the solid body and only seeks an efficient way to determine whether the structure equilibrium is stable or not. Various successful analytical tools have been developed for this task. In other circumstances, an accurate prediction of this energy transfer is critical in order to avoid high-amplitude vibrations of a system. In such cases, the solution is to keep the relative transfer of energy from the fluid to the structure as low as possible when compared to the damping capacity of the apparatus. Conversely, structures undergoing flutter, such as airfoils, could be conceived as devices to harvest energy from an incoming fluid, thus transforming the flapping airfoil into some sort of novel turbine. Unlike the previous case, one would want the positive flux of energy from the fluid to the structure to be maximized, and, at the same time, make sure the machine could resist to these high-amplitude, flow-induced oscillations over the long terms.

Following the pioneering work of McKinney and DeLaurier (1980) in the field of flapping-wing turbines, significant research on the subject has been performed by several groups in the last decade with a general goal of optimizing the concept. The increasing amount of publications on this matter (see review paper of Young et al. (2014)) is indicative of the rapidly growing interest towards the concept, which is justified by several advantages over the more conventional flow harvesters (see Guney and Kaygusuz (2010)). To state only a few of them, these bio-inspired turbines are not subject to the centrifugal stresses associated to the rotating blades found in most turbines. This makes the oscillating-foils devices structurally robust. Further, the oscillating foils sweep a rectangular

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flow window, which can be relatively wide and shallow. This is particularly interesting for the purpose of harvesting significant energy from rivers, especially those that are not very deep.

The promising potential of flapping foils as wind or hydrokinetic turbines has been confirmed both numerically (see Kinsey and Dumas (2006, 2008, 2012, 2014)) and experimentally (see Kinsey et al. (2011)) by the LMFN Laboratory (Laboratoire de Mécanique des Fluides Numérique) at Laval University. Several other groups also confirmed its potential, and the interested reader may refer to a recent review paper by Young et al. (2014) for an overview of the various concepts suggested and studied. Another recent review paper by Xiao and Zhu (2014) draws a clear portrait of the current state-of-the-art, and the main findings of several studies are gathered within this publication. In several of the concepts suggested, a rigid wing is mounted on a clever mechanical system in which the cyclic shape of the motion and the relation (phase lag) between the pitching, which is the angular motion, and the heaving, which is the translational motion, were enforced in such a way as to significantly increase the efficiency of the turbine, and the total energy it harvests from the flow (see Kinsey et al. (2011)). Among these systems, some involved a well-designed mechanical coupling between both motions, and this reduced the device to a single degree-of-freedom (DOF). Whether it has one or two DOFs, optimization of the energy harvester has typically been achieved through a direct implicit or explicit control on the functional shape, frequency and phase lag of the airfoil's motions in pitch and in heave. Energy harvesting efficiencies as high as 43% have been reported by Kinsey and Dumas (2014). Nevertheless, the mechanical components required to achieve this implicit or explicit control do add some mechanical complexity to the device, and this, in turn, may impair its *mechanical efficiency*, which should not be confused with the *energy harvesting efficiency*. A turbine concept not making use of such a mechanical coupling could therefore be greatly beneficial.

Recently, some research groups reported promising results concerning a simplified, semi-passive version of the flapping-foil flow harvester. In these semi-passive systems, the pitching motion of the foil is prescribed while the heave results naturally through the interaction of the foil with the flow and the supporting mechanism (see Shimizu et al. (2008), Zhu et al. (2009), Zhu and Peng (2009)). Energy harvesting efficiencies as high as 25% have been reported following numerical studies, thus confirming the interesting potential of this simplified mechanism. An experimental study has also been conducted by Huxham et al. (2012) in a water tunnel, and efficiencies around 24% have been reported.

According to Zhu et al. (2009) and to Kinsey and Dumas (2008), flapping-airfoil devices essentially harvest the flow through the heaving motion. This means that the pitching motion produces or incurs only modest inputs/outputs of energy in the mean, which suggests the concept of a further simplified, fully-passive system (see Zhu (2011)). This idea that the pitching motion could be fully autonomous in an energetic sense has been experimentally (see Poirel et al. (2008)) and numerically (see Lapointe and Dumas (2011)) validated by observing self-sustained, pitching-only motion of a wing at transitional Reynolds numbers.

In a simplified fully-passive system, both the heaving and the pitching motions are entirely determined through the fluid-structure interaction between the foil, the flow and the elastic supports. Large-amplitude, self-sustained oscillations have been experimentally observed for such a system (see Dimitriadis and Li (2009), Mendes et al. (2011), Poirel and Mendes (2011), Razak et al. (2011)). The relatively new idea of using a fully-passive system to harvest energy from a flow offers significant mechanical advantages over the preceding mechanisms at the cost of having no direct control over the motion of the foil. For a foil mounted on a rotational spring and a linear damper undergoing large-amplitude, cyclic oscillations, Peng and Zhu (2009) reported energy harvesting efficiencies up to 20%. Although the 2D numerical study was conducted at fairly low Reynolds number (Re=1,000), it revealed the potential of this new kind of turbine, and further optimization of this passive system is probably at reach. However, as mentioned by the authors of the aforementioned paper, the response of the airfoil to the flow excitation might be significantly different for higher Reynolds numbers more representative of real turbine applications, and this remains to be investigated.

The optimization of the fully-passive, flapping airfoil must be achieved by adjusting parameters of the apparatus having only an indirect effect on the motion of the foil, thus implying that a thorough understanding of the physics is critical. Note here that for the purpose of turbine applications, only cases for which limit-cycle oscillations (LCO) emerge are of interest. For such cases, the wing oscillates in a nonchaotic way with a single frequency for both DOFs, and the amplitudes of motion are relatively constant. This well-behaved motion of the airfoil is possible due to the nonlinearity of the aerodynamic forces, which is associated to the periodic dynamic stalling of the streamlined solid body (see Dowell et al. (2005)).

In this context of using a fully-passive, flapping airfoil as a wind or hydrokinetic turbine, Lapointe (2012), a former member of the authors' group, initiated a numerical study dealing with elastically-mounted, passive airfoils oscillating in transitional flows. The present investigation is an extension of this interesting work at higher, more practical Reynolds numbers. At this initial stage of the investigation, this paper aims to establish a proper FSI and optimization procedure, and to demonstrate the existence of local maxima of power extraction within the parametric space. A comprehensive parametric study is thus beyond the scope of the present work. Such study is ongoing and will be reported in a future paper together with the results of an experimental validation campaign. The present paper is thus divided as follows. The modeling and computational methodology is first introduced, followed by the presentation and the validation of the numerical solver. Then, an optimization of the turbine is presented along with a physical study of the mechanisms through which the performances are enhanced. Lastly, the main findings are summarized in a brief conclusion.

Before moving on to the next section, the reader should note that there remains some confusion in the literature on what a fully-passive, flapping-airfoil turbine really is. This is because some research groups consider that a device is fully-passive as soon as the motion is induced by the flow. Nevertheless, this is not strictly correct. This is because some devices make use of a mechanical linkage between both DOFs, thus imposing some constraints on the motion of the foils. However, actuators are not necessarily used in such cases, which means that the oscillations are entirely flow-induced. However, categorizing such devices as being fully-passive would certainly be misleading. In this work, the term *fully-passive* is exclusively reserved for devices where no actuators are present, and no mechanical linkage or coupling between the DOFs are used, thus for which both DOFs are freely responding unconstrained.