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Ground effect on the power extraction performance of a flapping wing biomimetic energy generator

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ABSTRACT

In this study the ground effect on the power extraction by a flapping wing based biomimetic energy generator was numerically investigated. The use of flapping wings, which derives inspiration from the study of biomimetics, has been considered as an alternative approach to developing an energy generation system that is completely different from the traditional turbine-based power generation unit. A NACA0015 airfoil, which is commonly used to model the wing cross-section, was placed in a two-dimensional laminar flow system and imposed with a harmonic plunge and pitch rotary motion. To carry out numerical simulations, the immersed boundary-lattice Boltzmann method was employed. At a Reynolds number of 1100 and with the position of the airfoil pitching axis at one third of the chord length from the leading edge, the influence of the clearance between the airfoil pitching axis and the ground ($c \le h_0 \le 5c$, c is the chord length of the airfoil), the amplitude ($h_m = 0.5c$ and c, $\alpha_n = 10^\circ$ and 20°) and frequency ($0.05 \le St \le 0.5$) of motion on the force behavior and power extraction were systematically evaluated. Compared to the situation in which there was no ground effect, the airfoil placed in close proximity to the ground gave improved power extraction performance. For given amplitude, as the clearance decreased the power extraction efficiency improved. The maximum efficiency improved by 28.6%. Moreover, it was found that the contribution to efficiency improvement was essentially from the increased plunging component of the power extraction, resulting from the generation of high lift force, rather than that of pitching.

1. Introduction

As a part of biomimetics, studies on the flying species in nature were initiated as early as the year 1500. For their excellent maneuverability, navigating skills and aerodynamic performance birds, insects and other such species constantly aroused curiosity and keen attention among the humans. The terrestrial bound species of animals keep in motion relying on friction from the ground, whereas the species in nature with abilities to be airborne execute their flight or hovering by flapping their wings to generate the necessary thrust and lift forces (Videler, 2005; Wang, 2005; Wu, 2011). Compared to the man-made fixed-wing aircrafts based on propulsion, the locomotion of the airborne species in nature is mainly attributed to the generation of a vortex wake that has the net effect of pushing the animal forward. Moreover, different kinds of wakes are

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formed at different flight speeds. By visualizing airflow around the wings of the hawk moth insect, *Manduca sexta*, Ellington et al. (1996) reported that the increase in high lift aerodynamic mechanism originated from the intense leading edge vortex (LEV) created by the dynamic stall. Several studies on propulsion by flapping wings have been widely conducted by experimental techniques and numerical simulations (Liu and Kawachi, 1998; Jones and Platzer, 1999; Dickinson et al., 1999; Wang, 2000; Sane and Dickinson, 2001; Rozhdestvensky and Ryzhov, 2003; Poelma et al., 2006; Heathcote et al., 2008).

In recent years due to the exponential increase in energy demands intensive efforts have been expended on the development of novel energy generation systems based on renewable energy. One typical example in this regard is the wind turbine, which extracts power from the wind by the rotating action of blades. However, the adverse environmental effects such as noise and potential hazards to birds from rotating blades have been discouraging in extensive application of wind turbines for power generation. Therefore, the biomimetic energy generators, which are based on the inspiration derived from perfect aerodynamic performance of the flapping wings, appear to hold promise. The concept of harvesting energy from the flapping wings could be traced to the work of Wu (1972), who indicated wavy flow is necessary for power extraction. However, McKinney and DeLaurier (1981) later found that an oscillating wing could equally extract power from uniform flow. This conclusion provided impetus for the accelerated development of flapping wing based biomimetic energy generators during the past few years (Jones and Platzer, 1997; Kinsey and Dumas, 2008; Peng and Zhu, 2009; Zhu, 2011; Ashraf et al., 2011; Xiao et al., 2012; Boragno et al., 2012; Zhu, 2012; Liu et al., 2013).

The propellers based on flapping wings require energy input to move air and the wake behind such propeller is found as the thrust type. In contrast, the wake behind such flapping wing of the energy harvester is of drag type. Based on the experimental evaluation of wakes behind a flapping foil, Godoy-Diana et al. (2008) established a flapping frequency–amplitude phase space to identify the drag–thrust transition line. To extract power with the flapping foils, it is necessary for the motion of foils is either of high frequency with small amplitude or low frequency with large amplitude. Currently, there are three types of power extraction systems based on flapping foil and these are classified in terms of their activating mechanisms. The first type is a system with imposed pitching and plunging motions and these have been broadly investigated. The studies on these systems, excluded the actuation mechanism from consideration (cost of power was not considered). The results from these studies, therefore, are mostly hypothetical. However, such approach is simple, easy to formulate mathematically and favored in the current research. Due to the specified pitching and plunging motions, the power extracted by these systems equals their hydrodynamic energy input. The second and third types respectively are the systems with imposed pitching and induced plunging motions (semi-activated systems) and the systems with self-sustained pitching and plunging motions. For the second type of systems, net power extraction is positive only if the power extracted from the plunging motion exceeds the power expended to activate the pitching motion. A different dynamic behavior may occur in the third type of systems. Among these response modes, only the periodic response is most suitable for power extraction. For comprehensive information on the flapping type energy generators, the reader may refer to the review paper of Xiao and Zhu (2014).

When a wing is placed in close proximity to the ground, the oncoming flows compared to free stream produce a higher lift and reduction in the induced drag. This well-known phenomenon is referred as the wing in ground (WIG) effect (Widnall and Barrows, 1970). Its underlying mechanism is that the pressure on lower surface of the wing increases when the distance between the wing and the ground is below a critical value. The WIG effect has been successfully applied to the racing cars. However, the studies on the ground effect were mainly concentrated on the fixed wing. Very limited information is available on the ground effect related to flapping wings. Moryossef and Levy (2004) investigated the flow field around a vertically oscillating airfoil near the ground using numerical methods. When the airfoil is in close proximity to the ground and oscillates at low frequencies, viscous effects dominate the flow field, whereas at high frequencies inviscid flow behavior is acceptable. Gao and Lu (2008) investigated the ground effect on normal hovering flight of an insect, in which the foil executed both translation and rotation. Recently, Truong et al. (2013) experimentally measured the aerodynamic forces and flow structures of a single flapping wing of beetle during takeoff. The literature survey indicated that, the ground effect has never been considered in evaluating the performance of flapping wing based biomimetic energy generator.

This paper reports the studies on the ground effect on the power extraction by a flapping wing based biomimetic energy generator. The numerical simulations were carried out using recently developed immersed boundary-lattice Boltzmann method (IB-LBM) (Wu and Shu, 2009). This method has been successfully employed to simulate a variety of moving boundary problems (Wu et al., 2010; Wu and Shu, 2011, 2012). A NACA0015 airfoil, which represents the cross-section of a wing, was considered in this work. Its flapping motion mode was induced through synchronous harmonic plunge and pitch rotation, on which the first type of existing flapping type energy generators is based. After selecting the Reynolds number and location of airfoil pitching axis, the effects of the distance between the airfoil pitching axis and the ground, the amplitude and frequency of oscillation on power extraction by the flapping wing were examined. Based on the numerical results obtained, the evaluation of ground effect on the force behavior as well as power extraction performance of the flapping wing was conducted.

2. Problem description and methodology

2.1. Problem description

In this study, a NACA0015 airfoil was used to model the wing cross-section with the flapping motion. As shown in Fig. 1, the foil which was placed in proximity to the ground experienced synchronous pitching and plunging motions. During this