03

Aperture Effect of Normal Hovering Flight in Close Proximity to the Ground

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Aerodynamics of a flapping foil at low Reynolds number in close proximity to the ground in aperture effect are studied by numerical simulations based on the normal hovering motion mode. A vortex street is interestingly generated by both ground and aperture effects and the rotation of the foil. The study reveals that the aperture takes a force-reduction effect and a large enough aperture effectively can remove the ground force-enhancement effect produced when the foil is in close proximity to the ground. This paper provides an effective method of optimizing foil-flapping flight design of flying robotics over a porous plane.

Keywords: aerodynamics; flapping foil; low Reynolds number; ground effect; aperture effect

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Wing flapping in air is a very interesting behavior of flying insect. Research and development of small flapping-wing robotics (for example, [1–3]) becomes a hot study area. Wing flapping produces lift/thrust of insect flying in air. The aerodynamic performance of the insect's wing flapping is helpful in understanding the insect's flight capabilities and for design of robotics that utilize the same principle.

The characteristics of flow around the insect's wing have been studied earlier. The effect on the insect's flying behaviors in close proximity to the ground has been studied by many researchers [4–8]. The ground was found to have a significant effect on the aerodynamic performance of a flapping foil. Specifically, there are three typical regimes of force behavior due to the ground effect, i.e., force-enhancement, force-reduction, and force-recovery regimes [5]. The mutational ground and different sized cylindrical obstacles produce different effects from the case in the ground effect [8,9]. It was found from the study about the effect of finite-sized platform on a flapping foil that, the position of the airfoil relative to the platform edge effectively influences the aerodynamic performance of the foil flapping, and furthermore, a reverse von Kármán vortex street due to the effect of finite-sized platform was found [10]. Naturally the ground is porous and there are apertures in a horizontal plate or the ground over which insects or robotic insects hover (Fig. 1). For example, bees usually flap their wings to cool the porous honeycomb. Some insects prefer to fly or hover close to the grassplot or a porous surface. The apertures in the horizontal plate or the ground are considered to have a significant effect on the aerodynamic performance of the wing flapping. To date, little work on the effect of apertures has been reported. In this paper, a two-dimensional (2-D) model is developed and the aerodynamics of flapping foil under the effect of an aperture in the horizontal ground are investigated.

Flapping motion of wings is usually periodic, and can be described with an approximate sinusoidal function. In this paper, the normal-hovering motion mode of 2-D foil flapping motion is used [3]. The equations that describe the position of the flap are:

$$x(t) = \frac{A}{2}\cos(2\pi f t) \tag{1}$$

$$\alpha(t) = \alpha_0 + \beta \sin(2\pi f t + \phi) \tag{2}$$

where, $x(t)$ is the location of the airfoil center, A is the stroke amplitude (i. e., the distance from the starting position of downstroke to the starting position of upstroke), $\alpha(t)$ is the foil's orientation with respect to the x axis, α_0 is initial angle of attack, which is equal to $\pi/2$ for the symmetry mode, β is the amplitude of pitching angle of attack, f is the frequency, ϕ is the phase difference between $x(t)$ and $\alpha(t)$, and t is the time. Here, the deformation of the foil in the air flow is not considered.

In nature, the flow around the flapping wings of insects during flight is always low-speed and laminar. In this paper, the unsteady-state flow is considered as an incompressible ideal gas, which can be described by the governing equations, including the Navier-Strokes equations and continuity equation:

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u}\cdot\nabla\mathbf{u} = -\frac{1}{\rho}\nabla p + \upsilon\nabla^2\mathbf{u} \tag{3}$$

$$\nabla\cdot\mathbf{u} = 0 \tag{4}$$

where, $\mathbf{u}$ is the air speed, p is the static pressure, ρ is the air density ($1\,\mathrm{kg/m^3}$), and υ is the dynamic viscosity of air. The lift and drag coefficients are expressed as, respectively,

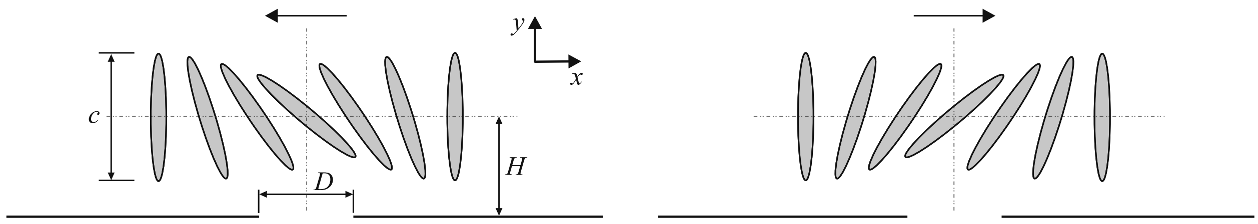

Figure 1. Sketch of a foil flapping in normal hovering motion over a horizontal ground with an aperture: (left) downstroke and (right) upstroke. c is the chord length, H is the height of the foil that is the distance from the chord center to the ground, and D is the width of the aperture.

$C_L = \frac{F_y}{0.5\rho U^2 c}$ and $C_D = \frac{F_x}{0.5\rho U^2 c}$, where, F_x and F_y are the horizontal and vertical components of air force on the foil, respectively, and U is the foil tip speed.

The ellipse-shaped airfoil having a chord length of 2.74 mm and the aspect ratio of 8 are used. The initial attack angle is 90°, the phase difference 0, and the flapping amplitude $2.8c$. The geometry of 2-D computational domain is a circle, which consists of a small internal circle with the radius of $4c$ and a large external annulus with the external radius of $20c$. The geometry is meshed by using ANSYS ICEM CFD. The grids in the internal block are denser than in the external block and the grids near the foil surface are refined again. User-defined functions (UDFs) are used in ANSYS FLUENT [11] to describe the motion of foil according to Eqs. (1) and (2). The Pressure Implicit with Splitting of Operators (PISO) algorithm is used to solve the coupling of pressure and velocity. Pressure is discretized with a PREssure STaggering Option (PRESTO) scheme, while the momentum equations are discretized with a second-order up-wind scheme. After conducting analysis of independence of results on grid number and time step length, we use medium grid size (101.22 thousand cells) and medium time step length of $T/400$. The simulation results are validated by comparing them with ref. [3].

By numerical simulations, compared to the flapping of foil in an open flow, when H/c is between 1 and 1.5, the ground has a force-enhancement effect on the time-averaged lift coefficient. When H/c is between 2 and 3, the ground has a force-reduction effect. While, when H/c is between 3.5 and 5, the ground has a force-recovery effect. can be The results are in good agreement with existing literature.

The force-enhancement effect reaches its maximum for $H/c = 1$ and the maximum force-enhancement effect becomes much stronger than the force-reduction effect and the force-recovery effect. In order to analyze the aperture effect on the aerodynamics of the flapping foil, different D/c values of $K = D/c = 0$, 1.5, 2 and 2.5 are selected when the foil is in close proximity to the ground. Fig. 2 shows the variations of lift and drag coefficients over one period for different D/c values and the case for infinite aperture (KK in abbreviation, also being the open flow case) for $H/c = 1$. Fig. 3 shows the vorticity field over one period for $D/c = 1$. As shown in Fig. 2, the peaks of the lift and drag coefficients decrease sharply for $H/c = 1$ due to an aperture. The reason is that a part of the vortex below the lower surface of foil flows through the aperture as shown in Fig. 3. The aperture then weakens the vortex pair, thus reducing the peaks of lift and drag coefficient curves. Furthermore, with an increase in the aperture size, the aperture effect becomes weaker because of weaker ground effect producing weaker force-enhancement effect. Interestingly, owing to rotation of the foil, a reverse von Kármán vortex street is formed below the aperture. Furthermore, when D/c is larger than and equal to 2.5, the lift and drag coefficients are close to that those for the KK, indicating that the large enough aperture basically can remove the strong ground effect.

In summary, a vortex street is produced by both ground and aperture effects in addition to the rotation of the foil. When the ground clearance is small enough, the ground has a force-enhancement effect. The aperture leads to the reduction of the lift and drag coefficients, which weakens the force-enhancement effect produced by the ground effect.

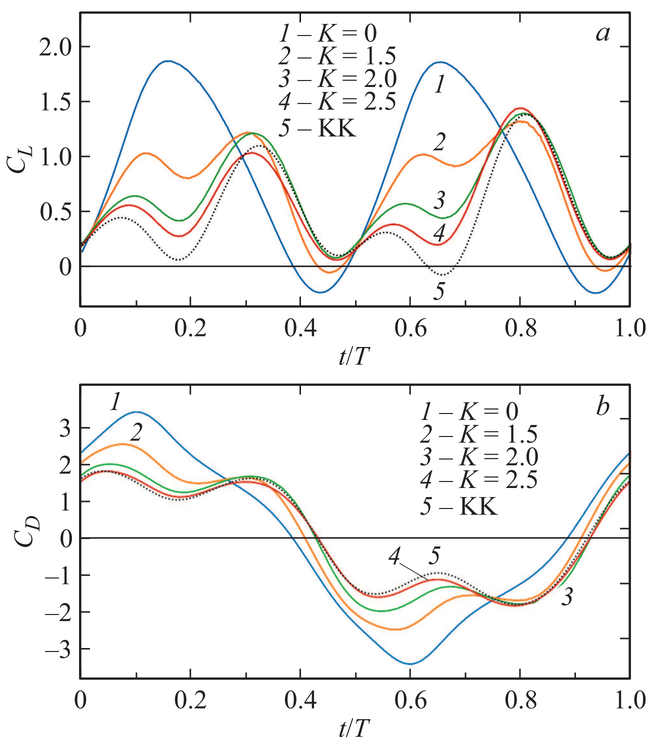

Figure 2. (a) Lift and (b) drag coefficients over one period for different $K = D/c$ values. t is the time and T is one period.

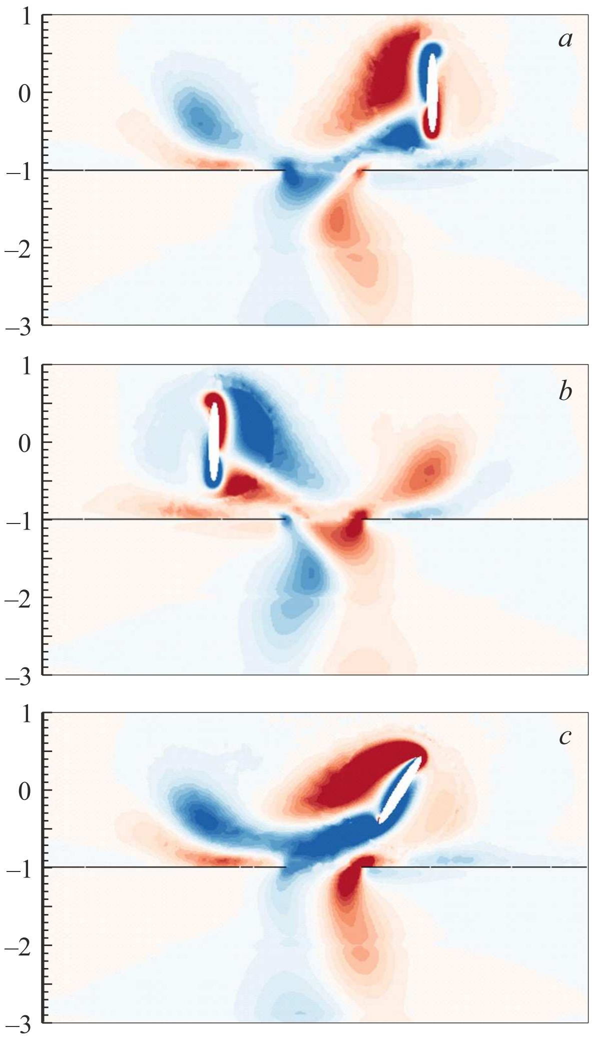

Figure 3. Vorticity field over one period for $K = D/c = 1$ and $H/c = 1$ at different times $t/T = (a)$ 0, (b) 1/2, and (c) 7/8. t is the time and T is one period.

This paper provides an effective method of weakening the ground force-enhancement effect for foil-flapping flight design and facilitates optimization of foil-flapping flight design over a porous plane.

Conflict of interest

The authors declare that they have no conflict of interest.

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