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Enclosure enhancement of flight performance

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Abstract We use a potential flow solver to investigate the aerodynamic aspects of flapping flights in enclosed spaces. The enclosure effects are simulated by the method of images. Our study complements previous aerodynamic analyses which considered only the near-ground flight. The present results show that flying in the proximity of an enclosure affects the aerodynamic performance of flapping wings in terms of lift and thrust generation and power consumption. It leads to higher flight efficiency and more than 5% increase of the generation of lift and thrust.

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Flight performance enhancement strategies such as formation and near-ground flights are frequently exploited by several biological systems, such as fish joining together in schools and birds flying in line and cluster formations low over oceans. Recently, there has been a great interest in the study of these flight situations from both the biological sciences and aerospace engineering research communities[1–7] due to their potential for significant improvement in flight performance in terms of aerodynamic load generation and energy savings.

Several studies have examined the possible exploitation of unsteady aerodynamic aspects associated with the ground effects of flapping flight.[1–7] For instance, flight of a small bird is investigated numerically by Su et al.[2] under the influence of the ground. It is observed that when the bird approaches the ground, the average lift force gradually increase while the average drag force decrease. Of interest, they found that the improved aerodynamic performance in flapping flight is much more significant than in steady flight. In a recent experimental study, Truong et al.[1] found that beetles take off without jumping which is uncommon for insects. In an attempt to explain this observation, they built a scaled-up electromechanical model of a flapping wing and examined the fluid flow around the beetle's wing model. The proximity to the ground was identified to be responsible for enhancing significantly the lift force generation. This enhancement lifts the beetle during takeoff which avoids jumping as was observed for other insects.

The understanding and characterization of the aerodynamic aspects of flapping flights under different situations, through numerical and experimental studies, are important in the design

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of engineered flying systems, such as micro-air vehicles (MAVs). These vehicles usually employ flapping wings as propulsion mechanisms to mimic bird flights and are designed to perform surveillance and intelligence missions in confined spaces (inside buildings, caves, or tunnels) where they may operate close to each other and near obstacles (e.g., ground, walls, and roofs). As such, the interactions between these vehicles with the surrounding environment can result in some aerodynamic aspects that need to be simulated, explained, and taken into consideration in the design of robust and efficient MAVs.

In this work, we present a numerical investigation of the enclosure effects on the aerodynamic performance of flapping wings. The unsteady vortex lattice method (UVLM) along with the image technique are used for the assessment of the aerodynamic quantities of flapping wings flying in enclosed spaces.

Aerodynamic modeling of flapping flight Pressure differences caused by acceleration- and circulation-based phenomena across the wing surface can generate loads, and we use UVLM to compute the loads generated. This accounts for unsteady effects, e.g., the growth of bound circulation, added mass forces, and the wake. UVLM applies only to ideal fluids, that is, incompressible, inviscid, and irrotational flows where we know the separation lines a priori. The fluid is required by UVLM to leave the wing smoothly at the trailing edge through imposing the Kutta condition.

The UVLM solver proceedures are:[8–10] (1) The wing surface is discretized into a lattice of vortex rings. There are four short straight vortex segments in each vortex ring, with a collocation point placed at the ring's center. We compute the absolute velocity induced by all discrete vortex segments following the Biot–Savart law. (2) A no-penetration condition is imposed at the collocation points. The normal component of the velocity due to wing-wing and wake-wing interactions as well as the free-stream velocities is forced to vanish at each collocation point. (3) In order to introduce vorticity to the wake, we shed vortex segments from the trailing edge. These vortices are moved with the fluid particle velocity and their individual circulation remains constant. (4) The pressure is evaluated at each collocation point based on the unsteady Bernoulli equation and then integrated over the wing surface to compute the aerodynamic forces and pressure.

UVLM does not account for viscous effects and the cases of flow separation happened in the leading-edge and extreme situations where compelling wing-wake interactions take place. In spite of these limitations, the use of UVLM remains adequate for the application of our interest.[11–13] For more details on the current implementation of UVLM along with verification and validation studies, the reader is referred to Refs. 8, 9, 14.

Simulation of enclosure effects To analyze the ground effect using UVLM, an effective ground plane is introduced into the model. This is achieved using the method of images.[15–17] In this technique, the vortex lattice representing the lifting surface (wing) and wake are mirrored about the ground plane. In the simulation, we place a mirror-image of each vortex segment (with inverted circulation) under the ground plane as shown in Fig. 1(a). In Fig. 2, we plot the actual and virtual wings and wakes where the color levels denote the vorticity circulation strength. The vorticity in the wake was generated on and shed from the wing at an earlier time. Thus, examining the wake pattern and vorticity distribution is helpful to gain insight into the generation of aerodynamic quantities. The pockets of highest circulation are observed in the wake aft of flapping wings during the downstroke. The vortex distribution of the virtual lattices modeling the image

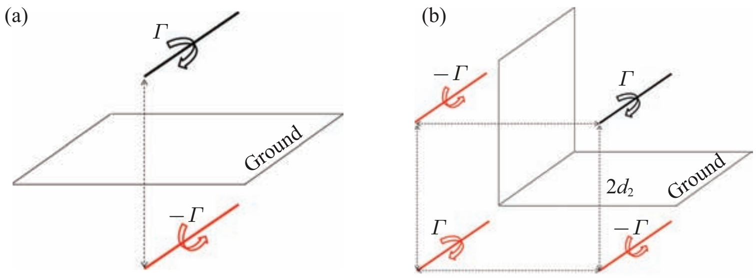

Fig. 1. Modeling approach of the enclosure effects: (a) ground effect and (b) corner effect.

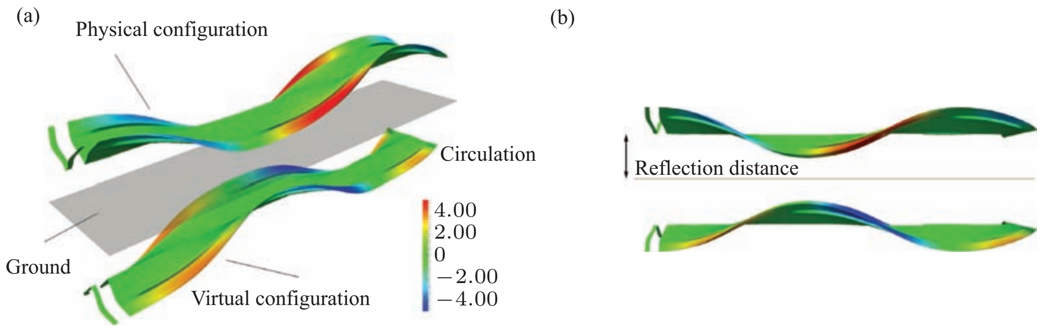

Fig. 2. (Color online) UVLM simulation of the physical and virtual wakes. (a) Perspective view and (b) side view.

lifting surface and wake create a secondary induced flow-field. The velocities at any point in the space induced by all vortex segments are added up. At the ground plane, the vertical component of the velocities induced by the actual and virtual wings cancel each other.

In Fig. 3, we show streamlines of the velocity field surrounding the actual and virtual wings. The no-penetration (or tangency) condition is satisfied along the actual and virtual wings and the ground. More information about the incorporation of the ground effect in the UVLM model can be found in Refs. 15–17. To the best of our knowledge, there are few experimental or numerical studies on the aerodynamic behavior of flapping wings in forward flights under ground effect,[18–20] however, there has been more interest to study this effect for hovering flights.[3–6] Thus, to verify the numerical predictions of the present aerodynamic model in simulating the ground effect, the results for the lift coefficient of the current vortex-lattice model are compared against those gotten by Katz and Plotkin[15] for a plunging wing under an incoming freestream and approaching the ground. The wing is rectangular with an aspect ratio of 4 and is placed $0.25c$ away from the ground and at a $-5°$ angle of attack. The plunging motion is assumed to be harmonic with a $0.1c$ amplitude and a reduced frequency $\kappa = c\omega/(2U_\infty)$ of 0.1. Here ω is the oscillation frequency, c is the chord length, and U_∞ is the freestream velocity. A comparison of the two sets of results is shown in Fig. 4. Both results agree very well. To compare, the same number of chordwise and spanwise elements was used. Refining the aerodynamic mesh showed little changes in the simulation results.

Enclosure effects on aerodynamic performance We consider the effect of the simultaneous proximity to the ground and a wall. To simulate these combined effects, we follow a similar approach to the one described above to model ground effects in which for each vortex segment,

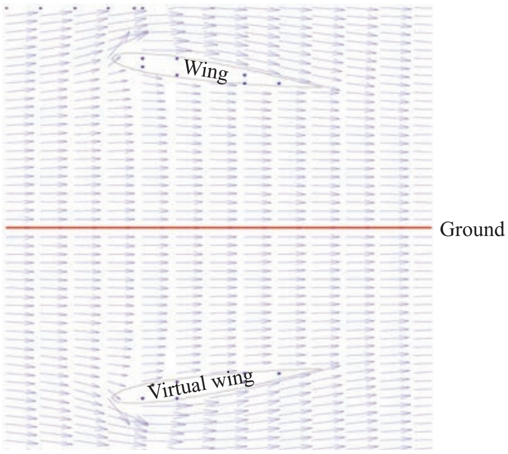

Fig. 3. UVLM simulation of the ground effect on the velocity field. Arrows denote streamlines.

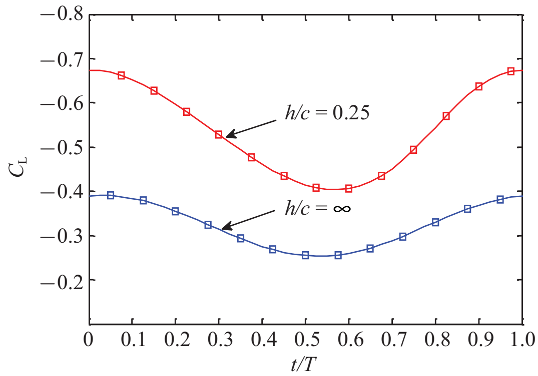

Fig. 4. Effect of the ground proximity on the lift coefficient during the plunging oscillation of a rectangular wing ($\kappa = 0.1$). Comparison with results obtained by Katz and Plotkin (represented by squares).[15]

we place three virtual vortex segments as illustrated in Fig. 1(b). The vortex segments images with respect to the ground and wall planes have inverted circulations while the vortex segment image with respect to the corner point has the same circulation as the actual segment. In this configuration, the no-penetration condition is satisfied at the ground and wall planes and both actual and virtual wings. In the subsequent analysis, we vary the distances of the flapping wings to the ground and wall and investigate the performance of the flight in terms of aerodynamic load generation and power consumption.

Here, we present results of a flapping wing interacting with an incompressible uniform flow and flying in an enclosed space. The wing has a NACA 83XX cross-sectional profile as studied previously by Ghommem et al.[9] The wing shape considered here was identified from an optimization study[9] that aims at maximizing the propulsive efficiency, defined as the ratio of the propulsive power over the aerodynamic power.[8] A perspective view of the wing shape is shown in Fig. 5(a) and the corresponding dimensions are presented in Fig. 5(b).

The wing shape is discretized into an aerodynamic mesh of 24 chordwise elements and 20 spanwise elements with a single knot space and a quartic approximation for the B-spline representation. More details on the shape representation are given in Ref. 9.

The symmetric flapping motion (about the wing root) is prescribed as $\phi(t) = A_\phi \cos(\omega t)$, where ϕ is the flapping angle and the flapping amplitude A_ϕ is set to hold a maximum flapping angle equal to 45°. Furthermore, the wing root is placed at a fixed angle of attack (pitch) of 5° and a reduced frequency equal to 0.1 is used. Figure 5(c) shows schematically the flapping angle and the angle of attack.

The variations of the lift and thrust coefficients for the flapping wing flying near and far from the ground are shown in Fig. 6. Clearly, the proximity to the ground magnifies the aerodynamic loads, in particular, when the wings approach the ground, i.e., at the end of the downstroke and the beginning of the upstroke.

The ground and the wall considered in the present study are treated as flat surfaces. The

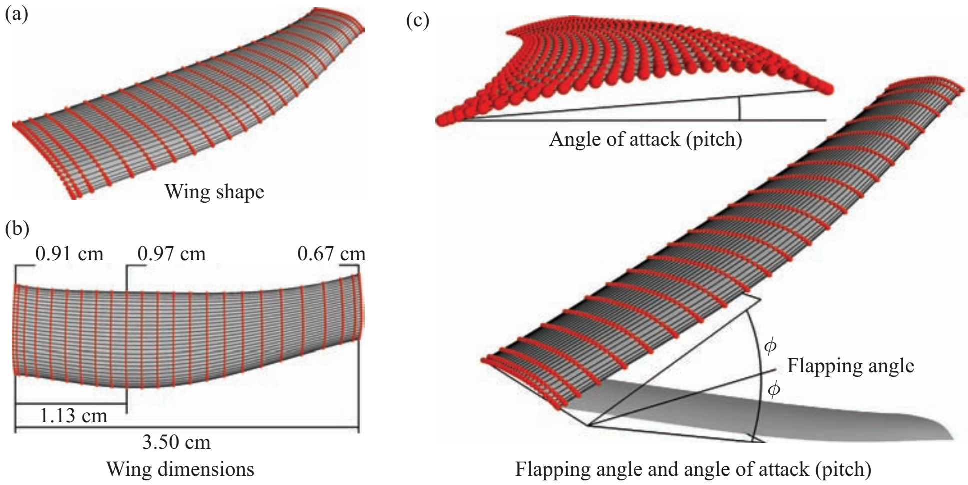

Fig. 5. Flapping wing configuration ϕ.

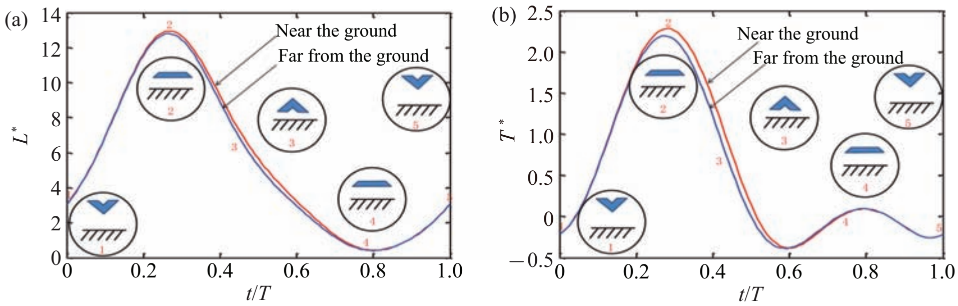

Fig. 6. Effect of the ground proximity on the (a) lift and (b) thrust coefficients of a flapping wing ($\kappa = 0.1$). The schematics shown inside the circles indicate the sequence of the phases along the flapping cycle and the proximity of the the wings to the ground.

distance from the ground, denoted by d_z, has values between 2.5 cm and 12.5 cm, and the distance from the wall, denoted by d_y, is between 3.5 cm to 13.5 cm. The distances between the wings and both the ground and the wall are taken from the base of the wings as shown in Fig. 7.

Figure 8 displays contours of the efficiency η and time-averaged lift L, thrust T, aerodynamic power P as function of the distances d_z and d_y from the ground and the wall, respectively. The contour plots show that approaching to the ground, i.e., as decreasing d_z, leads to higher values of

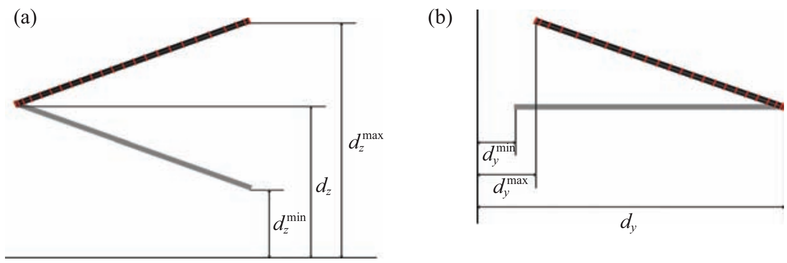

Fig. 7. Enclosed space dimensions. (a) Distance form ground (d_z) and (b) distance from wall (d_y).

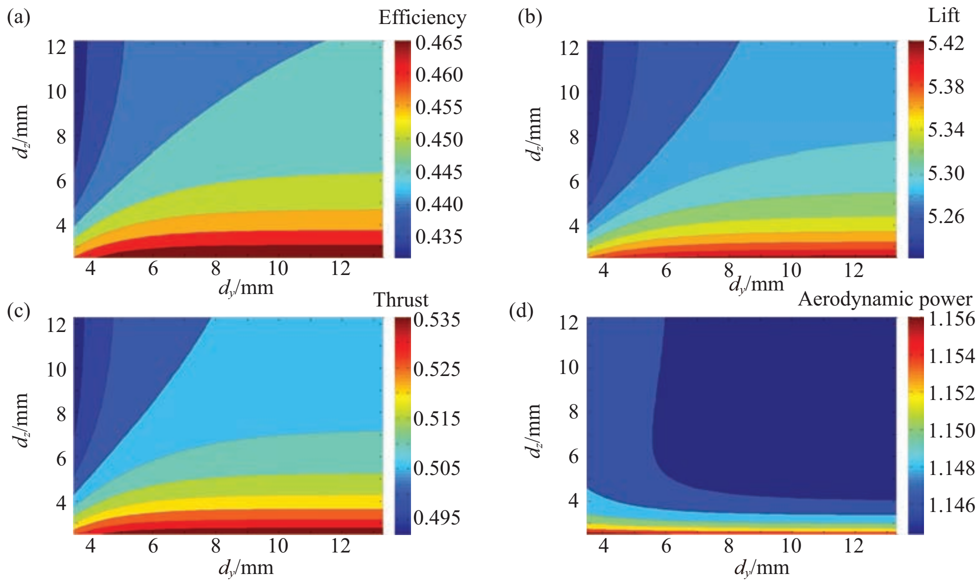

Fig. 8. (Color online) Enclosure effects on the propulsive efficiency, lift, thrust, and aerodynamic power of a flapping wing. d_z and d_y denote the distances from the ground and the wall.

efficiency and enables the generation of higher lift and thrust which may reach more than 5% increase while requiring slightly more aerodynamic power. Thus, one could conclude that flapping wings perform better when approaching the ground. For forward flights based on fixed wings, the ground was observed to destabilize the wings by initiating the onset of flutter at lower airspeed than that obtained when flying far from the ground[16,17] while our study shows that flapping wing vehicles may take advantage of being near the ground to improve their performance through increasing the propulsive efficiency. These observations reveal that the proximity to the ground should be taken into consideration for an efficient design of flapping wings for micro air vehicle applications. A different behavior is observed for the aerodynamic forces when approaching to the wall. As the distance to the wall d_y increases, the lift and thrust increase gradually and then settle down to the values L^*_∞ and T^*_∞, respectively, that correspond to the values obtained in absence of both ground and wall effects.

1. T. V. Truong, J. Kim, M. J. Kim, et al. Flow structures around a apping wing considering ground effect. *Experiments in Fluids* **54**, 1575 (2013).
2. J. Su, J. H. Tang, C. H. Wang, et al. A numerical investigation on the ground effect of a flapping flying bird. *Physics of Fluids* **25**, 093101 (2013).
3. T. Gao, X. Y. Lu. Insect normal hovering flight in ground effect. *Physics of Fluids* **20**, 087101 (2008).
4. J. M. C. Pereira, N. A. R. Maia, J. C. F. Pereira. A computational fluid dynamics study of a 2D airfoil in hovering flight under ground effect. *Computer Modeling in Engineering & Sciences* **49**, 113–141 (2009).
5. C. Chabalko, T. Fitzgerald, M. Valdez M, et al. Flapping aerodynamics and ground effect. AIAA Paper 2012-0420 (2012).
6. T. Gao, N. S. Liu, X. Y. Lu. Numerical analysis of ground effects on insect hovering. *J. Hydrody.* **20**, 17–22 (2008).
7. F. R. Hainsworth. Induced drag savings from ground effect and formation flight in brown pelicans. *Journal of Experimental Biology* **135**, 431–444 (1988).

8. M. Ghommem, M. R. Hajj, D. T. Mook, et al. Global optimization of actively-morphing flapping wings. *Journal of Fluids and Structures* **30**, 210–228 (2012).
9. M. Ghommem, N. Collier, A. H. Niemi, et al. On the shape optimization of flapping wings and their performance analysis. *Aerospace Science & Technology* **32**, 274–292 (2014).
10. M. Ghommem, N. Collier, V. M. Calo. PyFly: Fast, friendly framework for aerodynamic simulation. In: The European Aerospace Conference for Aero-space Science. Munich, July 1–5 (2013).
11. B. K. Stanford, P. S. Beran. Analytical sensitivity analysis of an unsteady vortex-lattice method for flapping-wing optimization. *J. Aircr.* **47**, 647–662 (2010).
12. M. S. Vest, J. Katz. Unsteady aerodynamic model of flapping wings. *AIAA Journal* **34**, 1435–1440 (1996).
13. T. E. Fritz, L. N. Long. Object-oriented unsteady vortex lattice method for flapping flight. *J. Aircr.* **41**, 1275–1290 (2004).
14. M. Ghommem. Modeling and analysis for optimization of unsteady aeroelastic systems, [PhD Thesis]. Virginia Polytechnic Institute and State University. Blacksburg (2011).
15. J. Katz, A. Plotkin. Low-Speed Aerodynamics. Cambridge University Press, Cambridge (2001).
16. A. O. Nuhait, M. F. Zedan. Numerical simulation of unsteady flow induced by a flat plate moving near ground. *J. Aircr.* **30**, 611–617 (1993).
17. A. O. Nuhait, D. T. Mook. Aeroelastic behavior of flat plates moving near the ground. *J. Aircr.* **47**, 464–474 (2010).
18. J. M. V. Rayner. On the aerodynamics of animal flight in ground effect. *Phil. Trans. Roy. Soc. B* **334**, 119–128 (1991).
19. P. C. Withers, P. L. Timko. The significance of ground effect to the aerodynamic cost of flight and energetics of the black skimmer (Rhyncops Nigra). *Journal of Experimental Biology* **70**, 13–26 (1977).
20. D. J. Willis, J. Peraire, J. K. White. A combined pFFT- multipole tree code, unsteady panel method with vortex particle wakes. *International Journal for Numerical Methods in Fluids* **53**, 1399–1422 (2007).