Ground effect on the aerodynamics of a flapping wing in forward flight: an experimental study

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Abstract

Purpose – Ground effect is one of the important factors in the enhancement of wing aerodynamic performance. This study aims to investigate the aerodynamic forces and performance of a flapping wing with the bending deflection angel under the ground effect.

Design/methodology/approach – In this study, the wing and flapping mechanism were designed and manufactured based on the seagull flight and then assembled. It is worth noting that this mechanism is capable of wing bending in the upstroke flight as big birds. Finally, the model was examined at bending deflection angles of 0° and 107° and different distances from the surface, flapping frequencies and velocities in forward flight in a wind tunnel.

Findings – The results revealed that the aerodynamic performance of flapping wings in forward flight improved due to the ground effect. The effect of the bending deflection mechanism on lift generation was escalated when the flapping wing was close to the surface, where the maximum power loading occurred.

Practical implications – Flapping wings have many different applications, such as maintenance, traffic control, pollution monitoring, meteorology and high-risk operations. Unlike fixed-wing micro aerial vehicles, flapping wings are capable of operating in very-low Reynolds-number flow regimes. On the other hand, ground effect poses positive impacts on the provision of aerodynamic forces in the take-off process.

Originality/value – Bending deflection in the flapping motion and ground effect are two influential factors in the enhancement of the aerodynamic performance of flapping wings. The combined effects of these two factors have not been studied yet, which is addressed in this study.

Keywords Ground effect, Bio-mimetic, FMAV, Experimental aerodynamic, Bending deflection mechanism

Paper type Research paper

Introduction

Flapping micro aerial vehicles (FMAVs) can provide many advantages because of their small size, low speed and high maneuverability (Shyy *et al.*, 1999). Flapping mechanism has been addressed in some numerical and experimental studies (Birch and Dickinson, 2001; Żbikowski *et al.*, 2004; Ansari *et al.*, 2010; Phillips and Knowles, 2011; Nguyen *et al.*, 2016; Lavimi *et al.*, 2019; Hojaji *et al.*, 2020) based on the real insect flight. Phan and Park (2019) comprehensively reviewed features and performance of different motions of insects. The early studies on birds' flight investigated the effect of flapping frequency, flight velocity and angle of attack (AOA) and wing geometry on aerodynamic forces. Muniappan *et al.* (2004, 2005) experimentally studied the effects of flapping frequency and flapping angle on the lift force. Their results showed that lift was enhanced and diminished by increasing flapping frequency and velocity of the wind tunnel, respectively. They have also discovered that the thrust force was not dependent on aspect ratio, whereas the lift force was dependent. Hu *et al.* (2010), in contrast with the study of Muniappan *et al.* (2004, 2005) indicated a rise in lift force by raising free stream velocity. In a parametric study, Gallivan and DeLaurier (2007) examined the effects of aspect ratio, planform shape and spar stiffness on lift and thrust. They showed that lift and thrust were augmented by increasing the aspect ratio. Also, the planform shape with a stiff spar performed better for the wing operation. Lin *et al.* (2006) stated that AOA reduction could increase the flight speed. They also pointed out that the wing area did not have a direct impact on the lift at the constant flapping frequency and wind speed.

Yang *et al.* (2009) fabricated a flapping wing using the wire cut process with electric discharge. This method benefits from reducing the structure weight, which ultimately enhances the aerodynamic performance. Yang *et al.* (2012) experimentally investigated aerodynamic forces by changing rib diameter, sweep angle and leading-edge shape. The results showed that a sweep angle of 30° backward on the wing and the leading edge with a trapezoidal tape strip provided more enhanced performance. In an experimental study on an FMAV

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(called TADBIR) in a wind tunnel, Mazaheri and Ebrahimi (2010, 2011) proved that the lift and thrust increased with the added flapping frequency. They also showed that lift and thrust increased and decreased by raising velocity, respectively. Nan *et al.* (2017) experimentally optimized the effects of aspect ratio and camber angle on the aerodynamic forces of a hummingbird-like flapping wing. They determined that higher aspect ratio and camber angle could produce more aerodynamic forces. In another research study, Huang (2019) experimentally optimized the geometric parameters of an eagle wing to maximize the production of lift and thrust (by nearly 3% and 12.5%, respectively). A hybrid code was developed by Yan *et al.* (2014, 2015) to assess the lift coefficient within large domains and study the effect of different aerodynamic models on the optimal kinematics of a hovering wing. They concluded that the unsteady model performed the best to provide optimal kinematics of FMAV.

Wing motions of birds during upstroke flight include folding, bending and twisting, and they stretch out their wings during downstroke motion. Each of these motions has different effects on aerodynamic forces. Hong and Altman (2008) stated that a thin spanwise cambered could produce a transient lift plate during the downstroke, and they analyzed the impact of spanwise flow on lift production. Wissa *et al.* (2012) installed a compliant spine into the leading edge spar at 37% of the wing half span. They simulated deflection of bending wing during the upstroke, showing that the lift increased by 16%, whereas input power decreased by nearly 45%. Some researchers used smart materials and investigated the effect of bending deflection along the wing spar on aerodynamic forces. In fact, with the bending motion of the bird, the wing splits into two different parts. In this regard, Forouzi Feshalami *et al.* (2019) designed and built a mechanism to provide bending deflection by the imitation of the black-headed gull. They experimentally examined the effects of wing bending deflection on thrust production, input power and power loading in hovering flight. The results showed that the performance of the bending deflection mechanism was better than that of a simple flapping wing. This study also compared the aerodynamic performances of wings with flexible, rigid and airfoil structures, showing the superiority of the airfoil structure. In another study, Forouzi Feshalami *et al.*(2019) simulated forward flight of the black-headed gull at different wind tunnel velocities. They tested the effects of flapping frequency, wind tunnel velocity and bending deflection angle (BDA) on aerodynamic forces, namely, lift, thrust and power loading. They found that the bending deflection mechanism was superior to a simple flapping wing. Also, with an increase in advance ratio, the aerodynamic coefficients decreased. Yu *et al.* (2020) numerically investigated the effects of spanwise bending and induced camber on lift, drag and endurance of the flexible wing. They used a fluid/structure interaction model to simulate an optimal flexible wing to produce the maximum aerodynamic endurance. The results illustrated that spanwise bending with induced camber provided aerodynamic endurance and decreased drag at high AOAs. Studies on the flexible wing have shown that wing flexibility increases the lift force of the MAVs (Syam Narayanan and Asad Ahmed, 2021). The motion of the two-section wings is closer to the real flight of birds since they have flapping, twisting and folding movements. Karimian and Jahanbin (2020) developed a new hybrid mechanism based on the bond graph approach for an elastic two-section flapping wing, whereby the twisting angles of the wing sections could be set. They evaluated the overall performance of the wings by calculating the average of lift, thrust and input and loading powers and could enhance the propulsive efficiency by 15%.

The ground effect has been addressed by many researchers because of its benefits to aerodynamics performance. Many numerical and experimental studies investigated the flight of wings underground effect (Rayner, 1991; Barber, 2006; Esmaeli *et al.*, 2010; Djavareshkian *et al.*, 2011; Azargoon *et al.*, 2019, 2020; Azargoon and Djavareshkian, 2021; Esmaeilifar *et al.*, 2017). The results of studies showed that the aerodynamic performance and the performance indices of flapping wings improved by flying near the surface (e.g. ground or water), which caused the air to be trapped between the wing and ground/water (Sibilski *et al.*, 2010; Zyluk *et al.*, 2016). This phenomenon increases the pressure gradient on the lower surface of the wing and increases lift force. Also, the ground prevents the creation of vortices on the wingtip that reduces downwash at the rear of the wing, so the vortex expansion stops, augmenting lift and diminishing drag (Ahmed and Sharma, 2005; Jung *et al.*, 2008; Tang *et al.*, 2013). In a three-dimensional (3D) simulation, Su *et al.* (2013) studied a flapping-flying bird underground effect in forward flight. Their results revealed that as the distance to the ground was reduced, the average lift and drag increased and decreased, respectively. Maeda and Liu (2013) simulated a 3D fruit fly hovering near the ground, discovering that ground effect led to lift production. Moreover, Kim *et al.* (2014) experimentally studied the hovering performance of Anna's hummingbirds under the ground effect. Their results indicated that the mechanical and metabolic energy was preserved when the distance to the ground was up to 1.1 times the wing length because the induced velocity decreased near the ground. Besides, Johansson *et al.* (2018) found that aerodynamic power was lower and more energy was preserved during the flapping flight of Daubenton's bats underground effect. Song (2021) examined a high-fidelity computational fluid dynamic model of a barn owl (Tyto alba) in gliding flight under the ground effect. He observed that the lift/drag ratio and span efficiency increased when the bird flew below a certain ground clearance (0.8 chord). In this study, the vortex induction was also modeled that showed the vertical flows were induced by the wake vortex, bound vortex, image wake vortex and image bound vortex. As the ground clearance was reduced, the drag production of the wake vortex and its image decreased, whereas the drag arising from the bound vortex and its image decreased after a slight increase.

Many studies have already been performed on the motions of birds; some of them addressed the ground effect for simplified geometries (without any bending deflection mechanism). As mentioned, Forouzi Feshalami *et al.* (2019) studied the design and construction of a bending deflection mechanism based on the black-headed gull. However, no study addressed the ground effect of flapping wings with the bending deflection mechanism. Therefore, in the present study, the wing with AOA = 0 degrees and BDAs of 0° and 107° is studied at different distances from the surface, different velocities and different flapping frequencies in a wind tunnel.

Figure 1 Mechanism designed in CATIA software

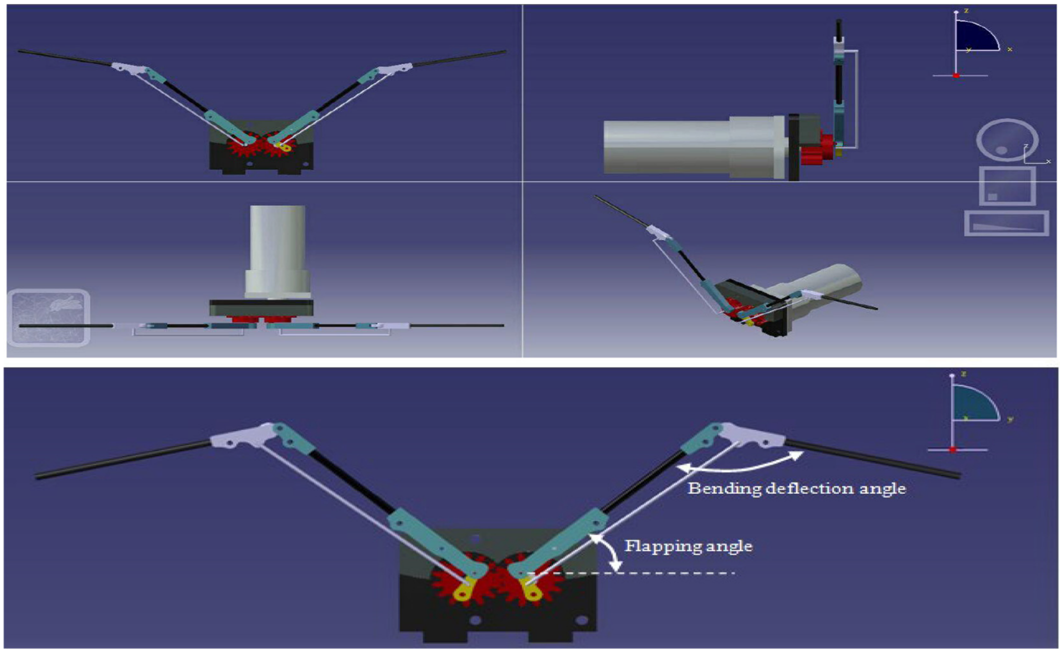
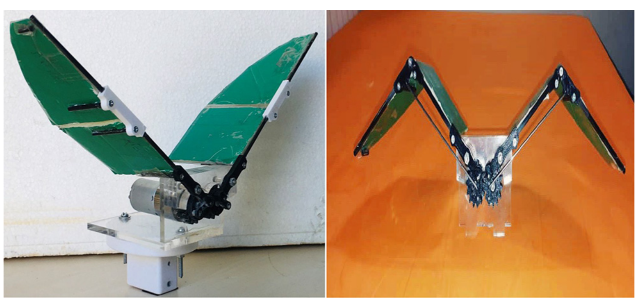


Figure 2 Wings designed, made and assembled on the mechanism by hand



(a) (b)

Notes: (a) Without BDA; (b) with BDA

Table 1 Geometric characteristics of wings

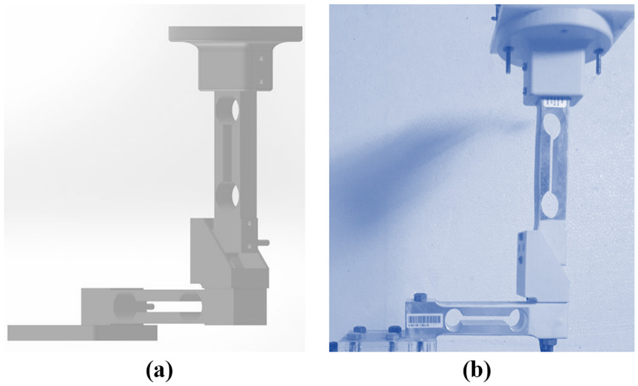
AR	Area (m^2)	Chord (cm)	Span (cm)	Wing length (cm)	Thickness (mm)
6.48	0.01	8	36	14.5	0.1

Experimental setup

In this study, a parallel single crank mechanism was designed in CATIA (shown in Figure 1). This mechanism converts the rotational movement of an electrical motor (ZhengKe motor ZGA42FH) to flapping motion (Gerdes *et al.*, 2012). To apply bend deflection of the wing during the upstroke, similar to the black-headed gull, the push rods were connected to the outer part of the wing by two joints. A 3D printer was used to print the mechanism components (Goh *et al.*, 2017), which were then assembled manually in the laboratory. Although there is a slight difference between the designed and assembled models, it is cost-effective due to simplicity and high speed (Manshadi, 2011). The minimum angle between the two parts of the wing has been defined based on BDAs, which was set by adjusting the distance between the crank and the pinned link on the pushrod. The starting point of bending was approximately 41% of the wing's semispan. The flapping frequency of the

Figure 3 Wings and flapping mechanism in the test section

Figure 4 (a) Mechanism designed and (b) manufactured for load cells



mechanism varied by changing the output voltage of a direct current power supply.

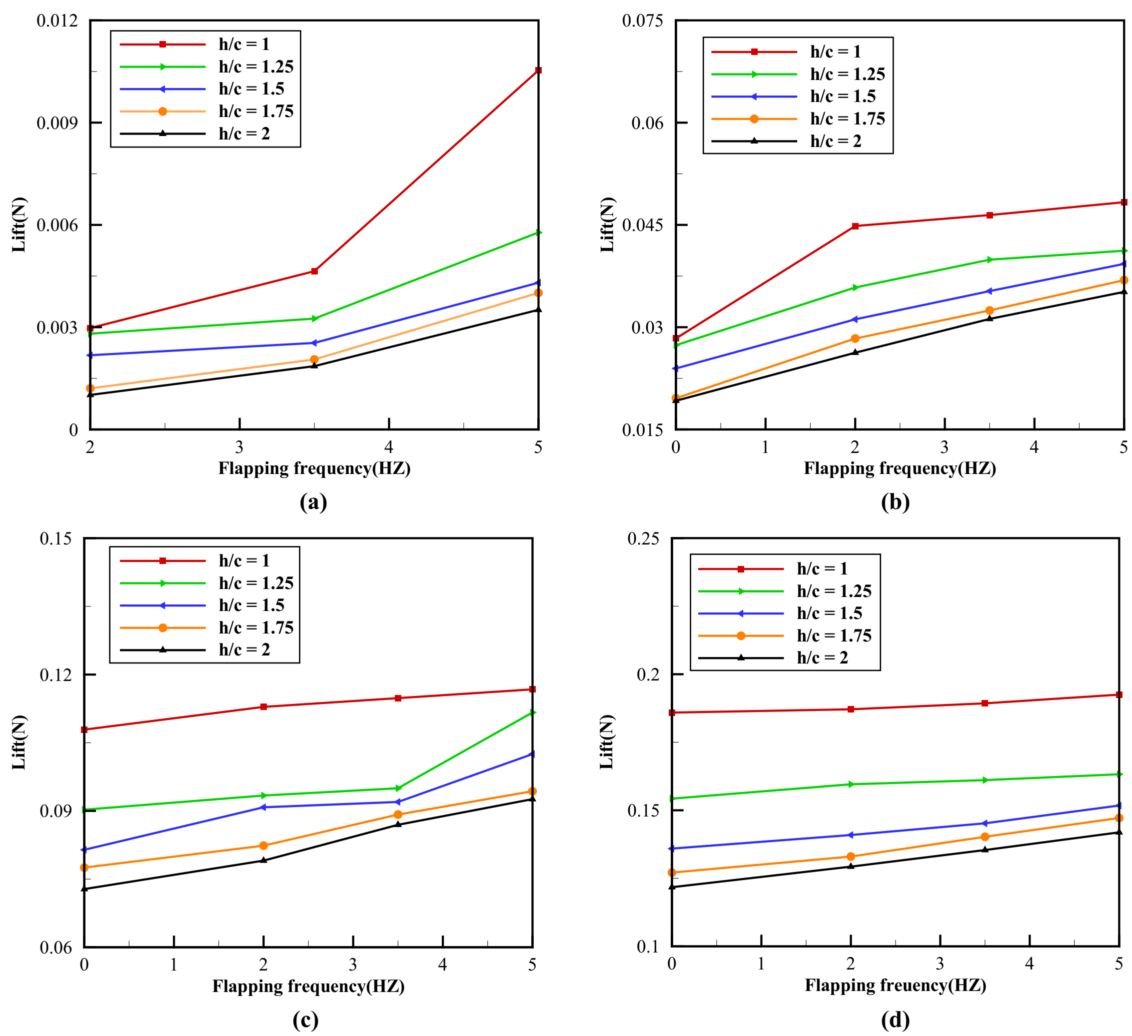
The wings, based on the wings of the black-headed gull, were also designed in CATIA software and then built by hand and assembled on the mechanism (see Figure 2). The information of the geometrical specifications of the wing are listed in Table 1.

Wind tunnel and measurement tools

An open-circuit low-speed wind tunnel with a closed test section of 120 cm × 100 cm was used in this study (Figure 3). The experimental tests were performed at different distances of wing root from the test section floor, which was dimensionalized with the chord (i.e. h/c), different tunnel wind velocities (i.e. 0, 3, 5 and 7 m/s) and different flapping frequencies of 0, 2, 3.5 and 5 Hz.

Many factors caused unfavorable conditions to reach the accuracy of tests and results, e.g. high turbulence intensity. The turbulence intensity of the wind tunnel was 0.3% at a velocity of 5 m/s. Results of an investigation by Mueller (2000) showed that turbulence intensity of less than 1% had an insignificant effect on lift and drag. To measure instantaneous lift and thrust, two one-dimensional strain gauge load cells with the capacities of 3 and 6 kg (model Bongshin OBU-N49106 and

Figure 5 Variations of lift versus flapping frequency for different h/c and BDA = 0°; wind tunnel velocities of (a) V = 0 m/s; (b) V = 3 m/s; (c) V = 5 m/s; and (d) V = 7 m/s



OBU-N50170, respectively) were used. Errors due to their nonlinearity (Mehraban *et al.*, 2021), reproducibility and hysteresis were less than 0.02% of their capacity. The relative error of these force sensors was below 0.4%. The calibration of the load cells was done by known static weights. Because the load cells are composed of strain gauges that record forces in the form of voltage, and to convert this voltage into force, calibration was done by known static weights. The voltage measured with the load cells was amplified using an amplifier (model Dacell DN-AM100). All signals were read with a data acquisition board (model Advantech PCI-1710HG). The noise of motor vibrations and flapping motions could cause errors, which were filtered using a low pass filter with a cut-off frequency of 15 Hz. According to Figure 4, the location of the load cells is designed in the CATIA software and manufactured by a 3D printer. Finally, the printed components are assembled.

Results and discussions

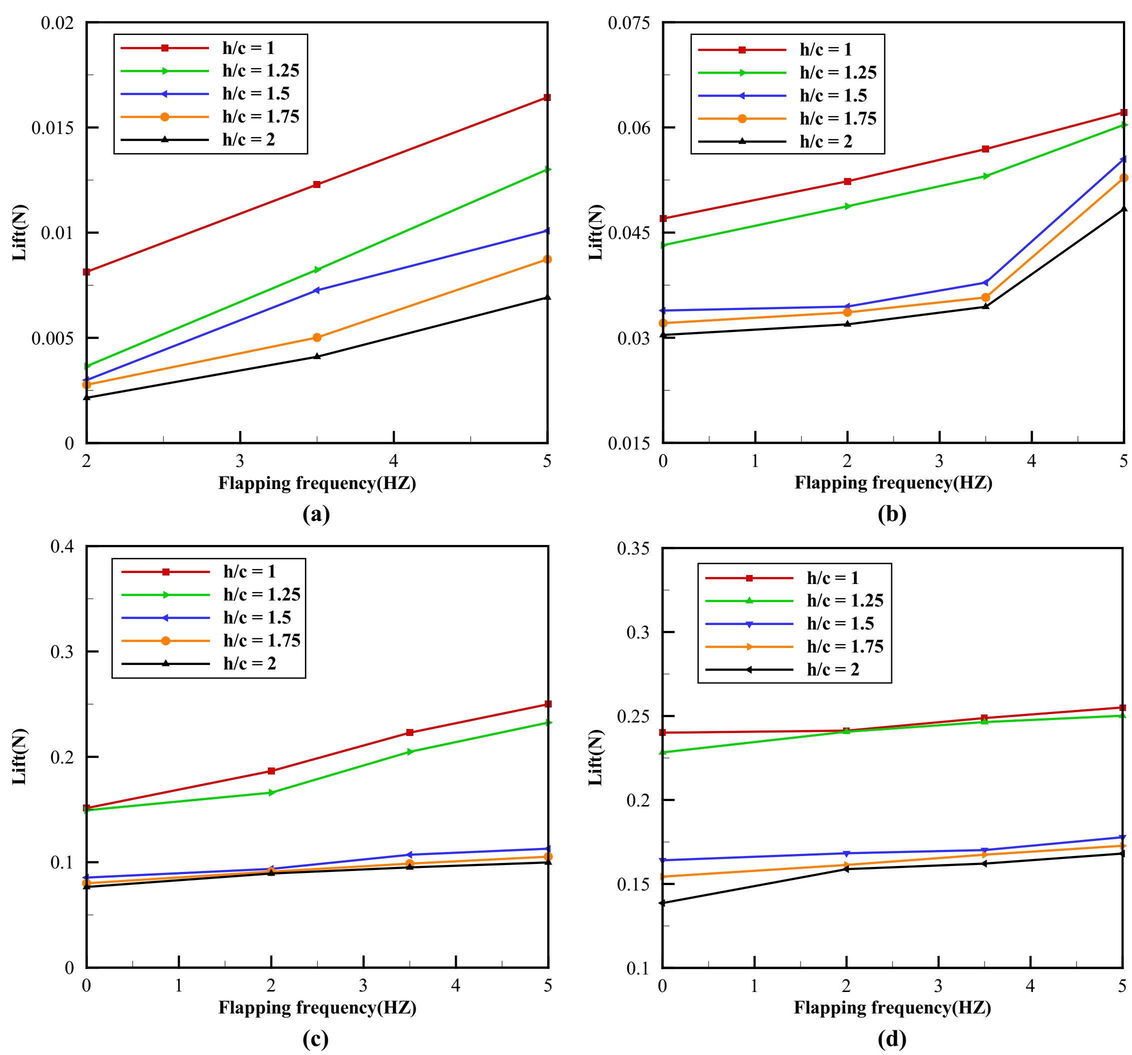
In this experimental study, a flapping mechanism of the black-headed gull was investigated in wind tunnel during forward flight. The results were obtained for different distances from ground (h/c = 1, 1.25, 1.5, 1.75, 2), flapping frequencies of 0, 2, 3.5 and 5 Hz and wind tunnel velocities of 0, 3, 5 and 7 m/s.

Lift generation

Flapping motion is caused by creating flapping frequency in the flapping mechanism. Some vortices form at the wing edge due to the flapping motion. As the frequency is raised, the flapping effect is more dominant, and, in turn, more vortices form, leading to an increase in lift. Also, the maximum vertical force occurs at the end of the downstroke, where vortices reach their maximum volume. Then, due to vortex shedding at the beginning of the upstroke, the vertical force is reduced. Since the positive lift in the downstroke is higher than the negative lift in the upstroke (which is due to gravity), a positive lift is obtained when forces in the upstroke and downstroke are summed.

Figure 5 depicts the variations of lift versus flapping frequency and h/c in forward flight at BDA of 0° for different wind tunnel velocities. As can be observed, the lift force was

Figure 6 Variations of lift versus flapping frequency for different h/c and BDA = 107°; wind tunnel velocities of (a) V = 0 m/s; (b) V = 3 m/s; (c) V = 5 m/s; and (d) V = 7 m/s



enhanced with an increase in flapping frequency (in all types of flights) and wind tunnel speed (in forward flight) for all distances (h/c), which was more highlighted at higher flapping frequencies. These results were consistent with the results reported by Hu *et al.* (2010), (Lin *et al.* (2006) and Mazaheri and Ebrahimi (2010, 2011). It can be seen that the maximum lift occurred at the closest distance from the surface (h/c = 1) and the ground effect increased with a rise in flapping frequency for all cases. The reduction of distance caused the air to be trapped between the surface under the flapping wing and the floor of the test section. The pressure gradient increased on the lower surface of the flapping wing, and then the pressure difference of the top and bottom surfaces of the wing increased (Azargoon *et al.*, 2019, 2020; Esmaeilifar *et al.*, 2017) causing a rise in the lift production. The spread of vortices was prevented for the wing underground effect, which was another reason for lift augmentation. These results agreed with the studies by Su *et al.* (2013) and Maeda and Liu (2013).

Figure 6 shows the variations of lift force versus flapping frequency and h/c in forward flight of the flapping wing at BDA of 107° for different wind tunnel velocities. The lift generation was elevated by increasing flapping frequency and velocity and decreasing h/c. It also can be seen that generation lift increased by using the bending deflection mechanism. Using the bending deflection mechanism, the relative area of wings perpendicular to the flapping motion was reduced during the upstroke, and the generation of the negative lift was lowered. During the downstroke motion, due to the creation of vortices and a low-pressure region over the upper surface of the wings, a positive lift was generated, being consistent with the results by Forouzi Feshalami *et al.* (2019). These effects were strengthened when the flapping wing was close to the surface, especially at h/c = 1 and 1.25, i.e. more lift was produced.

Net propulsion

Some vortices form and detach in the wing edge due to flapping motion. In addition to the lift force, these vortices cause a force component in the flow direction. However, since drag and thrust cannot be separated in a flapping motion, the thrust reported in this research is the summation of the former two forces.

Figure 7 Variations of thrust versus flapping frequency for different h/c and BDA = 0°; wind tunnel velocities of (a) V = 0 m/s; (b) V = 3 m/s; (c) V = 5 m/s; and (d) V = 7 m/s

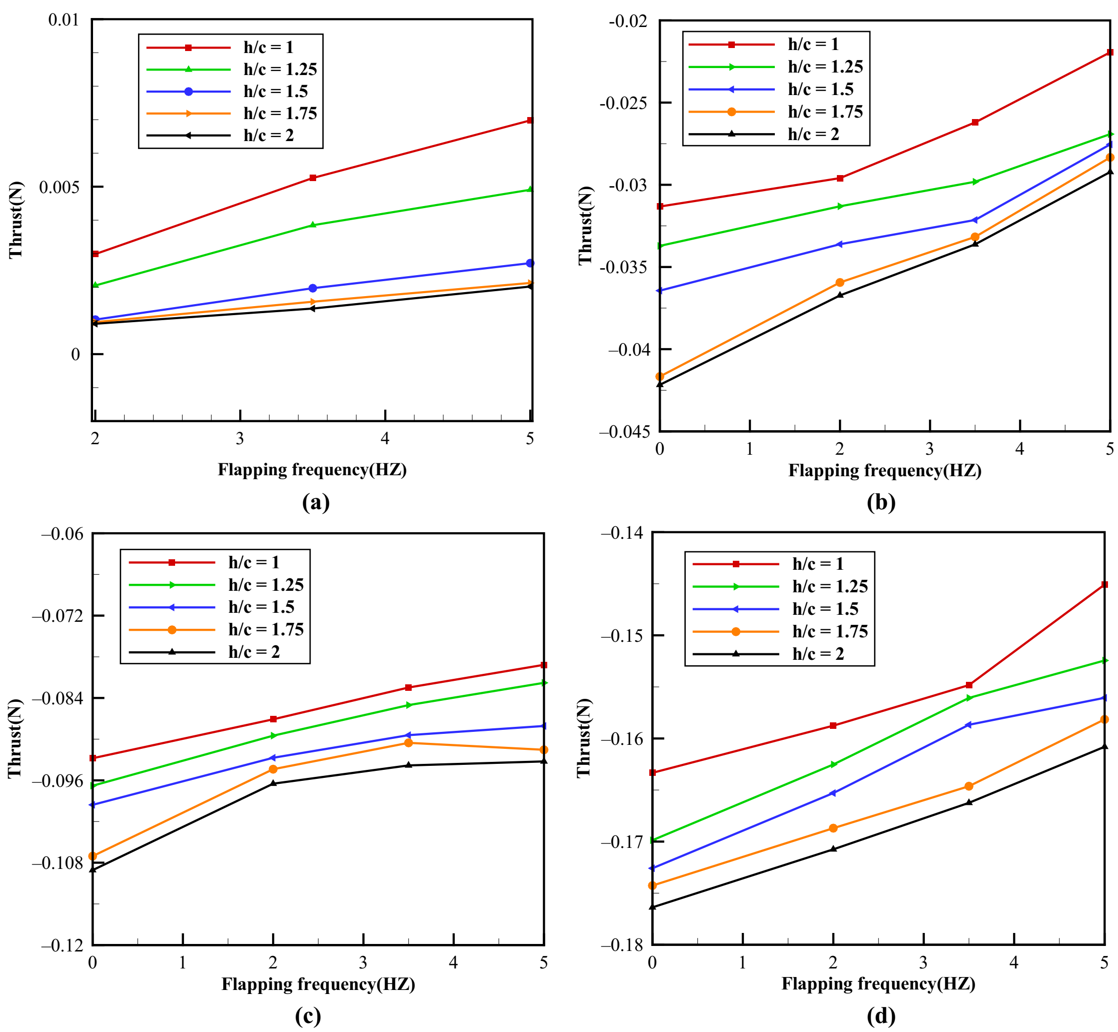


Figure 8 Variations of thrust versus flapping frequency for different h/c and BDA= 107°; wind tunnel velocities of (a) V = 0 m/s; (b) V = 3 m/s; (c) V = 5 m/s; and (d) V = 7 m/s

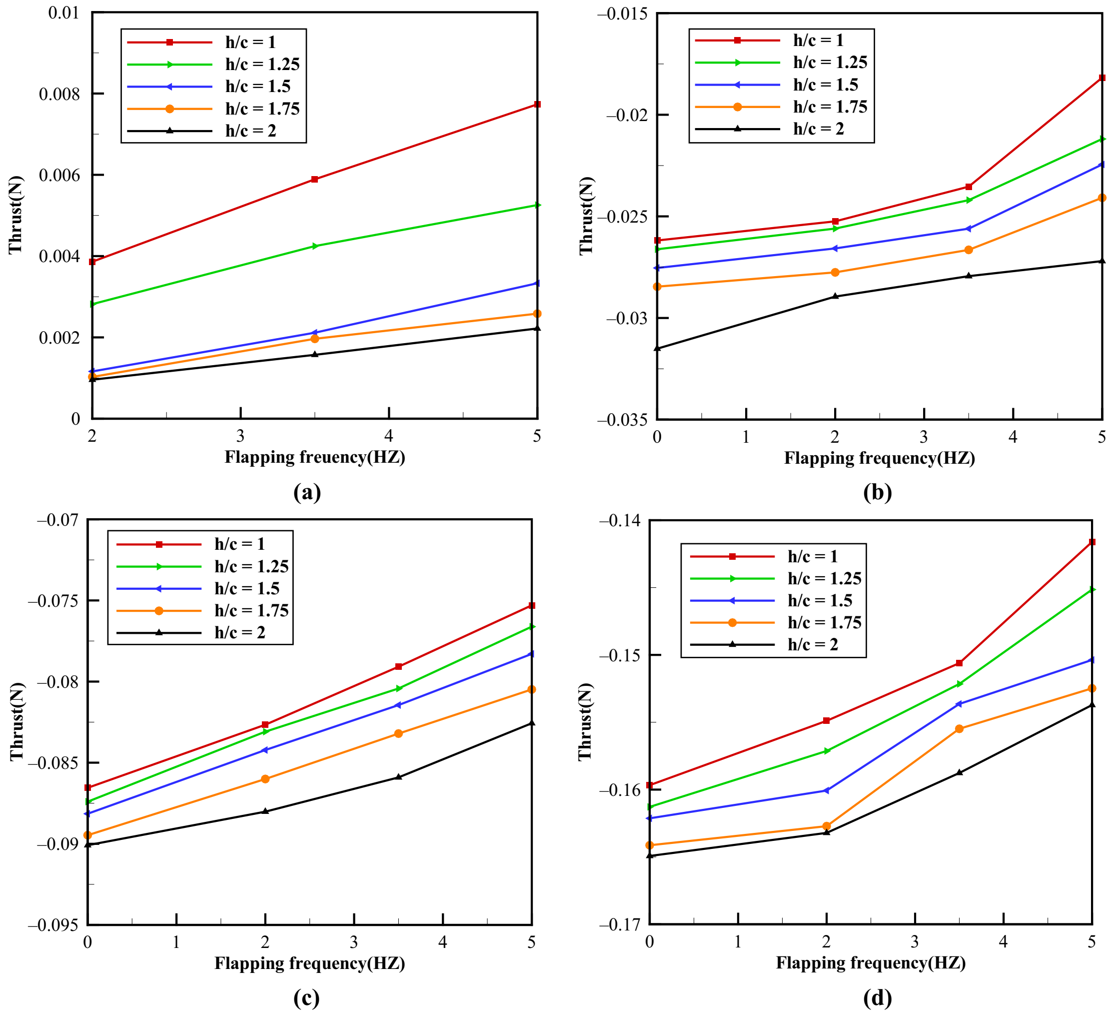
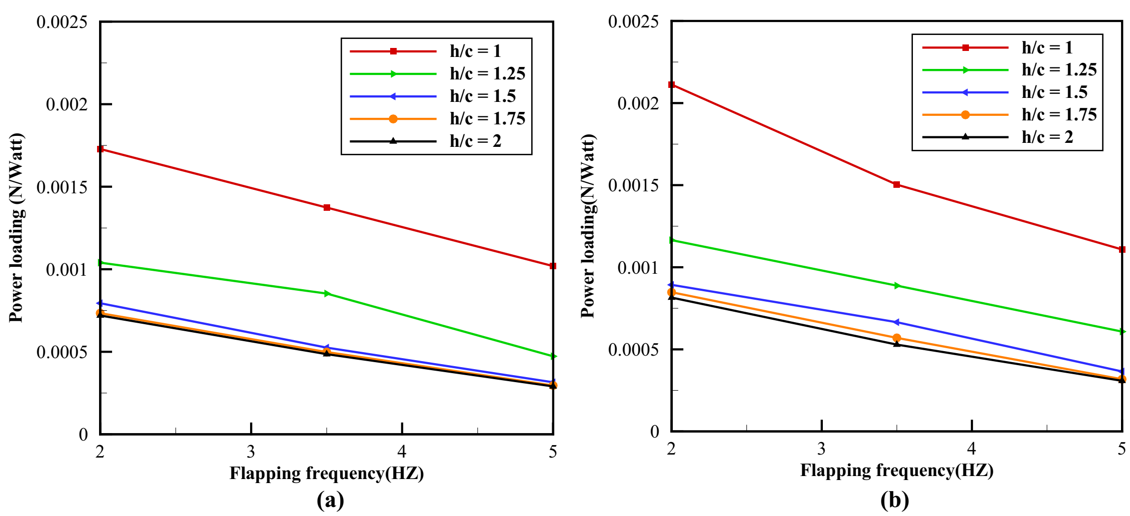


Figure 9 Variations of power loading versus flapping frequency for different h/c



Notes: (a) BDA = 0°; (b) BDA = 107°

Figures 7 and 8 report the results of the effects of flapping frequency, wind tunnel velocity and h/c on the thrust force of the flapping wing with BDAs of 0° and 107°, respectively. As shown in Figure 7, the thrust generation of the flapping wing increased by raising flapping frequency, whereas it was reduced by an increase in velocity for all h/c. This increment was more tangible at higher flapping frequencies. Also, a slight thrust production occurred at v = 0 m/s. It is noteworthy that the negative values of the thrust stand for the drag. Therefore, increasing the wind tunnel velocity reduced the thrust due to the drag force increase. Similarly, according to Mazaheri and Ebrahimi (2010, 2011), the thrust generally behaves incrementally by increasing flapping frequency even at high velocities. Furthermore, as can be observed in Figure 7, a decrease in h/c caused thrust generation. In other words, the ground effect decreased the drag force of the flapping wing. This thrust production is due to the reduction of vortex expansion in the ground, agreeing with the results of Su *et al.* (2013) and Song (2021). As can be observed in Figure 8, the thrust generation was raised by increasing flapping frequency and reducing h/c, whereas it decreased by increasing velocity for all cases. These results are similar to BDA = 0. According to Figure 8, using BDAs of 107° has a positive impact on thrust force generation. In this condition, BDAs and ground effect are two factors that increase thrust force. As a result, generation thrust is more than a flapping wing with BDA = 0, even close to the surface at all types of flights.

Power loading

The ratio of thrust to input power is defined as loading power, which is important to evaluate the performance of the flapping mechanism and flight endurance. Figure 9 indicates variations of power loading versus flapping frequency of simple flapping and bending deflection mechanism for different h/c. As shown in the figure, the power loading of both mechanisms (BDA = 0° and 107°) decreased by increasing flapping frequency at all distances (h/c). The maximum rate of power loading occurred at h/c = 1 and h/c = 1.25 ranked second. For h/c > 1.25, its effect on power loading decreased until it almost disappeared at h/c = 2. This agrees with the results obtained by Kim *et al.* (2014) about saving energy using ground effect. They posited that the main reason for saving energy is the reduction of induction velocity, which can be met using the ground effect. The loading power increased by applying bending deflection mechanism [see Figure 9(b)], more than that of BDA = 0°, due to the higher thrust generation and lower input power.

Conclusion

This study investigated the ground effect on the aerodynamics of a flapping wing with AOA = 0° and BDA of 0° and 107° at different flapping frequencies and velocities in forward flights. For this purpose, the experimental tests were conducted for different distances from the ground (i.e. h/c = 1, 1.25, 1.5, 1.75, 2), flapping frequencies of 0, 2, 3.5 and 5 Hz and wind tunnel velocities of 0, 3, 5 and 7 m/s. The points obtained from this research are summarized as follows:

- Lift increased with a decrease in distance from the ground. The maximum lift occurred at the closest distance from the surface (h/c = 1) and ground effect increased with an increase in flapping frequency in forward flight. Lift generation was augmented using the bending deflection mechanism. This effect was strengthened when the flapping wing was close to the surface, especially at h/c = 1 and 1.25.
- Ground effect decreased drag force of flapping wing and increased thrust. Using BDA of 107° had a positive impact on thrust generation for all cases.
- The maximum power loading occurred at h/c = 1 and h/c = 1.25 ranked second. For h/c > 1.25, its effect on power loading decreased until it almost disappeared at h/c = 2.

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Further reading

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Appendix. Nomenclature

AOA = angle of attack (°);
AR = aspect ratio;
BDA = bending deflection angle (°);
C = chord (cm);
FMAV = flapping micro aerial vehicle;
H = distance from surface (cm);
H/C = distance from surface (cm)/chord (cm);
I = current;
INF = infinite;
P = power;
R = resistance;
V = wind tunnel velocity; and
VOL = voltage.

Subscripts

C = circuit;
FM = flapping mechanism;
Ps = power supply; and
R = resistor.

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