Exploring a bumblebee-inspired power-optimal flapping-wing design for hovering on Mars based on a surrogate model

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Abstract
While rovers are of importance for Mars exploration in terms of various surveillance, surface rovers may encounter great challenges due to rough terrain and complex turbulent environment on Mars partly because aerial vehicles have difficulties to stay airborne due to the extremely low atmospheric density. Flights of surface rovers on Mars share the aerodynamic similarity with insect flights on earth in terms of low Reynolds number flow regime. Motivated by that insects can achieve remarkable flapping-wing aerodynamic performance in force production, flight stability and maneuverability under highly unsteady environments, we here proposed a bumblebee-inspired flapping-wing design for Mars surface rovers. We developed a power-efficient aerodynamic model by combining a surrogate model and a bioinspired dynamic flight simulator for hovering flight in a parametric space comprising wing shape and wing kinematics to explore feasible design points and some optimal solution with the power output minimized. Our results indicate that an enlarged wing model inspired by bumblebees is capable of sustaining hovering flight on Mars with a set of aspect ratios and wing kinematics and an optimal design point is found to correspond with a power output of 0.0509W, which may provide a novel and feasible biomimetic design for flapping-wing aerial vehicles on Mars.

Keywords: Mars, Bumblebee, Computational fluid dynamics (CFD), Surrogate model, Hovering

Nomenclature

\[O_b\] origin of body-fixed frame
\[O_w\] origin of wing-fixed frame
\[x_b\] x-axis of body-fixed frame
\[x_w\] x-axis of wing-fixed frame
\[y_b\] y-axis of body-fixed frame
\[y_w\] y-axis of wing-fixed frame
\[z_b\] z-axis of body-fixed frame
\[z_w\] z-axis of wing-fixed frame
\[\varepsilon\] wing to body mass ratio
\[c_m\] mean chord length
\[l\] wing length
\[m\] total mass
\[m_b\] body mass
1. Introduction

Mars exploration has been attracting a cross of talents for several reasons. For one, many are focusing on the possibility of human settlement on Mars (Fogg, 1993). The existence of plentiful soil and ice implies that there might be past lives on it (McKay, et al., 1996). The planet is also close to earth in terms of temperature and gravity, rendering it the most habitable planet in the solar system for human beings. For another, Mars contains a variety of mineral resources and preserved geologic record of early earth (Liu, et al., 2013), answering both the industrial demands and the question of how life originated and evolved on earth.

In the past decades, various orbiters, rovers and other platforms have been developed and sent to Mars. Mars surface is rough with complex terrains containing various craters, valleys and layers (Liu, et al., 2013), which normally hinders the mobility of surface vehicles. Moreover, the atmospheric density of Mars is 1.593x10^{-2} kg/m^3, approximately 1.3% of that on earth, which enhances the difficulties for conventionally designed flying vehicles to achieve stable flights and safe landing on Mars. Such extremely low atmosphere density leads to an extremely low Reynolds number of a flying vehicle on Mars, roughly 1.593% of that on earth, under the assumption of the same flight speed, size and viscosity. The two-order drop in Reynolds number thus results in a remarked change in aerodynamics of the aerial vehicles between earth and Mars: a conventional fixed or rotary wing flyer on earth that normally operates at high Reynolds numbers identical to a fully developed turbulent flow will encounter great challenges of low Reynolds number and large-scale separated flows on Mars in terms of less effective angles of attack, greater drag forces, and
instability against wind gust (Shyy, et al., 2008). On the other hand, this implies that the flights of aerial vehicles on Mars very likely share the aerodynamic similarity with insect flights on earth in terms of low Reynolds number flow regime.

Motivated by that insects can achieve remarkable flapping-wing aerodynamic performance at low Reynolds numbers in force production, flight stability and maneuverability under highly unsteady environments (Liu, et al., 2016), recently researchers have been exploring possible designs for flapping-wing surface rovers on Mars with consideration of the advantages that insect-inspired micro air vehicles can land and take off vertically, benefiting from robust flight stability and wind-gust rejection. In 2013, it was pointed out that bio-inspired flapping-wing micro air vehicles could be an option of feasible surface rovers to achieve special missions on Mars (Liu, et al., 2013). It was reported that a bumblebee with scaled-up wings might be able to produce enough vertical force on Mars (Bluman, et al., 2017). In 2018, a numerical simulation of the bumble-bee-inspired model with enlarged revolving wings with consideration of dynamic similarity was carried out, showing that the model could carry a payload as much as 100% of its body mass (Pohly, et al., 2018). They further investigated the effects of flapping amplitude and flapping frequency on vertical force production, concluding that increasing flapping amplitude led to a reduction in power consumption in the design space. A 2D Navier-Stokes equation solver was further employed to capture the unsteady flapping aerodynamics of the bumblebee model (Bluman, et al., 2018), showing that the majority power required was due to the wing inertia. In this respect, bumblebees could be a good model over other insects because of their much lower wing-to-body ratio of 0.4 ~ 0.52 % while capable of sustaining hovering with a heavy payload (Zhang and Liu, 2018). In 2019, it was proposed that a flapping-wing design inspired by bumblebees, namely, the “Marsbee” (Kang, 2019), shows the potential of achieving hovering flight on Mars compared to rotary wing vehicles (Pohly, et al., 2019).

In this study we aim at analyzing numerically the feasibility of a bumblebee-inspired flapping-wing design for Mars surface rovers to achieve power-efficient hovering flights on Mars. We developed an integrated computational model by combing a surrogate model and an in-house bioinspired dynamic flight simulator for hovering flight in a parametric space to explore feasible design points and some optimal solution with the power output minimized for flapping-wing aerial vehicles. We first present a power-efficient design for the bumblebee-inspired flapping-wing model in a parameter space comprising wing morphology and kinematics, which can produce sufficient vertical forces while having a minimum power output. An extensive discussion is then given on its capabilities for hovering flights on Mars. We finally conclude by summarizing the features and potential of the biomimetic design as well as future challenges in Mars surface rovers.

2. Methods

We built up an integrated computational framework by combining a bioinspired dynamic flight simulator (Liu, 2009) and a surrogate model (Queipo, et al., 2005). In this framework as described in the following sections three variables of interest comprising a parametric space and twenty-one computational cases are selected for simulations. The period-averaged vertical forces and powers are classified based on the surrogate model-based method and utilized to sort out the design points where the vertical forces are large enough to sustain a hovering flight on Mars while achieving a minimum power output.

2.1 A bioinspired flight dynamic simulator

We employed a biology-inspired dynamic flight simulator (Liu, 2009), which is versatile, easily integrating the modeling of realistic wing-body morphology, realistic wing-body kinematics, and unsteady aerodynamics in insect flight. A multi-blocked, overset-grid method is utilized to deal with complex wing-body geometries; a kinematic model is capable of mimicking realistic wing-body kinematics of flapping flight. A fortified finite-volume method (FVM)-based Navier-Stokes (NS) solver for the dynamically moving multi-blocked, overset-grid system is employed, which has been verified by a variety of benchmark tests (Liu, 2009). Fig. 1 illustrates the morphology and kinematic models of a bumblebee and coordinate systems. Three coordinate systems are presented: \( o_xo_yo_z \) fixed onto the body, and \( o_xo_yo_z \) onto the wing. The wing kinematics is defined by three flapping angles with respect to the stroke plane: the positional angle \( \psi \); the elevation angle \( \theta \), and the feathering angle \( \chi \) in terms of
geometric angle of attack (AoA) of a wing. The body kinematics can be represented by the body angle and the stroke plane angle \( \beta \). The Reynolds number is defined as \( Re = c_m U_{ref} / \nu \), where \( \nu \) denotes the kinematic viscosity of Martian air (\( \nu = 0.942 \times 10^{-3} \text{ m}^2 \text{s}^{-1} \)) with the atmospheric density of \( \rho = 1.593 \times 10^{-2} \text{ kg/m}^3 \), \( c_m \) the mean chord length as reference length, and \( U_{ref} \) the mean wing tip velocity as reference velocity being defined as \( 2 \phi l f \), which is determined by wing beat frequency \( f \), stroke amplitude \( \phi \) and the wing length \( l \). A wing-to-body mass ratio is introduced as \( \varepsilon = m_w / m_b \), where \( m_w \) denotes the mass of two wings and \( m_b \) the mass of body, respectively. The reduced frequency \( k \) is given by \( k = \pi c_m f / U_{ref} \) and Mach number is defined as \( M_a = U_{ref} / U_{msad} \), where \( U_{msad} \) is the speed of sound on Mars, approximately 244.8 m/s (Shrestha, et al., 2016).

2.2 A bumblebee-inspired model on Mars

This study uses a realistic bumblebee (Bumbis ignites) model as a baseline for morphological and kinematic models of its hovering flight (Fig. 1(a), Table 1). The bumblebee’s wing length is 15.2 mm and the mean chord length is 4.1 mm; the wing beat frequency \( f \) is 136.0 Hz and the stroke amplitude \( \phi \) is 139.36 deg. Body angle is 45 deg. and stroke plane angle \( \beta \) is about 0 deg. (Zhang and Liu, 2018; Kolomenskiy, et al., 2019). A multi-blocked, overset grid system around a bumblebee body-wing model with a background Cartesian grid system are depicted in Figs. 2 (a) – 2 (b) while Figs. 2 (c) - 2 (d) gives the time courses of flapping-wing kinematics of the bumblebee models on earth and a ‘virtual’ bumblebee on Mars. The wing kinematics of the ‘virtual’ bumblebee was adjusted so that the enlarged wings will not overlap with each other at the tips. The new wing kinematics is obtained based on the original wing kinematics with only one parameter changed, which represents the amplitude of feathering, as shown in Table 2. The Fourier series are given in Eqs. 1-3, where \( \psi_{en}, \psi_{sn}, \theta_{en}, \theta_{sn}, \chi_{en}, \chi_{sn} \) are Fourier coefficients and summarized in Table 2 for the original wing kinematics (Table 1 (a)) and the “virtual” wing kinematics (Table 2 (b)), respectively. On Earth cases, the change induces loss in vertical force, but the loss is not great, which means the altered kinematics is approximately viable for hovering. On Mars cases, the kinematics of the “virtual” case is applied on the base case and all the simulations are done with the wing kinematics on “virtual case”.

\[
\psi(t) = \sum_{n=0}^{m} [\psi_{cn} \cos(2n\pi ft) + \psi_{sn} \sin(2n\pi ft)]
\]

\[
\theta(t) = \sum_{n=0}^{m} [\theta_{cn} \cos(2n\pi ft) + \theta_{sn} \sin(2n\pi ft)]
\]

\[
\chi(t) = \sum_{n=0}^{m} [\chi_{cn} \cos(2n\pi ft) + \chi_{sn} \sin(2n\pi ft)]
\]
Table 1 Wing dimensions, kinematic parameters and wing-to-body mass ratios of four insects (Shyy, et al., 2010) (Kolomenskiy, et al., 2019).

| species               | \( c_m \) (mm) | \( l \) (mm) | \( f \) (Hz) | \( \phi \) (Deg.) | \( R_e \) | \( \beta \) (Deg.) | \( \varepsilon \) (%) |
|----------------------|----------------|--------------|--------------|------------------|--------|------------------|-------------------|
| fruit fly (Drosophila melanogaster) | 0.78           | 2.39         | 218          | 140              | 126    | 45               | 0.6               |
| honeybee (Apis mellifica)       | 3.0            | 10.0         | 232.1        | 90.5             | 1412   | 45               | 0.5               |
| hawkmoth (Manduca sexta)       | 18.3           | 48.3         | 26.1         | 114.6            | 5885   | 40               | 5.2               |
| bumblebee (Bumble ignites)      | 4.1            | 15.2         | 136.0        | 139.36           | 2748   | 45               | 0.4               |

Table 2 Fourier parameters for a bumblebee. (a) Bumblebee kinematics on Earth. (b) Bumblebee kinematics on Mars.

(a)  
| \( \psi_{cn} \) | \( \psi_{cn} \) | \( \theta_{cn} \) | \( \theta_{cn} \) | \( \chi_{cn} \) | \( \chi_{cn} \) |
|----------------|----------------|------------------|------------------|----------------|----------------|
| 0.32995        | -              | 0.21582          | -                | 0.02522        | -              |
| 1.18343        | -0.06342       | 0.00182          | 0.00795          | -0.09402       | -1.20174       |
| 0.05142        | -0.00092       | 0.03776          | -0.00466         | -0.00644       | -0.05717       |
| 0.01247        | -0.01209       | -0.01703         | -0.01648         | -0.00691       | -0.15243       |

(b)  
| \( \psi_{cn} \) | \( \psi_{cn} \) | \( \theta_{cn} \) | \( \theta_{cn} \) | \( \chi_{cn} \) | \( \chi_{cn} \) |
|----------------|----------------|------------------|------------------|----------------|----------------|
| 0.32995        | -              | 0.21582          | -                | 0.02522        | -              |
| 1.18343        | -0.06342       | 0.00182          | 0.00795          | -0.09402       | -0.48000       |
| 0.05142        | -0.00092       | 0.03776          | -0.00466         | -0.00644       | -0.05717       |
| 0.01247        | -0.01209       | -0.01703         | -0.01648         | -0.00691       | -0.15243       |

Fig. 2 A multi-blocked, overset grid system around (a) a bumblebee body-wing model with (b) a background Cartesian grid system. Flapping-wing kinematic models of a bumblebee on (c) earth and a (d) ‘virtual’ bumblebee on Mars. \( t \) denotes the time in a period, while \( T \) denotes a flapping period.

Here we conduct a scaling analyses on the relationship between vertical aerodynamic force, wing length, mean chord length, and flapping frequency. The period-average vertical aerodynamic force may be defined as

\[
F_z = \frac{1}{2} C_{Fz} \rho U_{ref}^2 c_m l
\]

where \( C_{Fz} \) denotes the vertical aerodynamic force coefficient, \( \rho \) the atmospheric density, \( U_{ref} \) the reference velocity, \( c_m \) the mean chord length, \( l \) the wing length, and \( F_z \) the vertical force, respectively. Given the reference velocity as
\[ U_{\text{ref}} = 2 \varphi l f \]  
(5)

where \( \varphi \) presents the stroke amplitude and \( f \) the flapping frequency, respectively, the vertical aerodynamic force can be expressed as

\[ F_z = 2C_{Fz} \rho f^2 \varphi^2 c_m l^3 \]  
(6)

Thus, in order to generate greater vertical forces, we may adjust wing kinematics of flapping frequency and stroke amplitude, and/or enlarge the wing area. Note that the aspect ratio and the wing shape may also have impacts to some extent.

Given the gravitational acceleration on Mars, \( g_m = 3.73 \text{ m/s}^2 \), and the mass of the bumblebee, \( m_{bb} = 392.5 \text{ mg} \) (Zhang et al., 2018), the weight of the bumblebee on Mars can be calculated as

\[ F_z = m_{bb} g_m \]  
(7)

which results in a value of approximately 1.46mN. Since the atmospheric density on Mars is approximately one-hundredth of that on earth, the bumblebee-on-earth-inspired model (Fig. 2, Eq. (6)) could not produce enough vertical force to stay airborne on Mars. Based on Eq. (6) we can obtain a scaling relation between vertical aerodynamic force and the wing length \( l \), the mean chord length \( c_m \), and the flapping frequency \( f \), i.e., \( F_z \sim c_m f^2 l^3 \). In this study we thereby selected and adjusted these three parameters as design variables to work on a feasible design capable of achieving hovering flights on Mars. Note that we excluded the stroke amplitude from the design variables but kept it unchanged, to explore the effects of the 3 main variables first. Furthermore, with consideration of the low wing-to-body mass ratio of bumblebee (0.4\%) (Table 1), we took a strategy to enlarge the wing in a way of morphological similarity. Note that the wing enlargement may cause increasing in air drags and inertial loads, which may lead to further requirements in terms of material and structural strength as well as driving system. Given the fact that the majority power required in an enlarged flapping-wing model is due to the wing inertia (Bluman et al., 2018), and that even with the wings enlarged double uniformly in mean chord length and span length, the wing-to-body mass ratio turns out to be merely up to 3.2\% of the total mass, this wing-enlargement strategy would not lead to a significant increase in inertial power. Therefore, as the first step we believe that such strategy is reasonable to evaluate the feasibility of the bumblebee-inspired design for Mars surface rovers in terms of its hovering capability and aerodynamic performance.

After a process of trial and error on selecting the three parameters we obtained a feasible design, namely, the basic case as illustrated in Fig. 3 with \( l = 32.55 \text{ mm} \), \( c_m = 10.8 \text{ mm} \), and \( f = 140 \text{ Hz} \), which could create a period-average vertical force of 1.48mN large enough to support the weight (1.46mN) of the bumblebee model on Mars. With respect to the bumblebee-inspired wing models on Mars, in order to avoid numerically inappropriate grid intersection between two wing-based grids, we made slight adjustments on the wing length and mean chord length as well as the feathering amplitude with a value of 0.48 rad (see the ’virtual’ bumblebee on Mars in Fig. 2 (b)). Note that such adjustments were applied to all other cases and thus keep the consistency to ensure the surrogate model-based optimization process reasonably.

The total power output \( P_{\text{total}} \) can be estimated by a summation of aerodynamic power \( P_{\text{aero}} \) and inertial power \( P_{\text{iner}} \) using the following equations:

\[ P_{\text{total}} = P_{\text{iner}} + P_{\text{aero}} \]  
(8)

\[ P_{\text{iner}} = \sum_{i=1}^{n_1} m_i a_i v_i \]  
(9)

\[ P_{\text{aero}} = -\sum_{i=1}^{n_1} F_{\text{aero},i} v_i \]  
(10)

where \( m_i, a_i, v_i \) denote the mass, acceleration and velocity of the \( i \)-th mesh, respectively; \( n_1 \) and \( n_2 \) represent the total number of surface elements and block elements of the models in the simulator (Liu, 2009).
Fig. 3 Wing and body morphologies at nine typical design points with the mean chord length $c_m$ and the wing length $l$ varying around a basic case of $c_m = 10.82$ mm and $l = 32.55$ mm by ±25% identical to a magnification factor of 0.75, 1.0 and 1.25, respectively.

### 2.3 Surrogate model-based power optimization

With respect to the three design variables of the wing length, the mean chord length, and the flapping frequency, we constructed a series of 21 cases as summarized in Table 3 with nine typical design cases as shown in Fig. 3, while applying a surrogate model combining with the CFD models to explore an optimal solution in terms of power minimization in the parametric space of the three design variables.

The surrogate model (Queipo, et al., 2005) is an easy and fast method to predict the outcome of a parametric space in a manner of optimization. It includes: 1) specifying a design of numerical experiments including 21 points in toto in a parametric space comprising three parameters of wing length, mean chord length and flapping frequency; 2) numerical simulations at design points; and 3) constructing a surrogate model based on the simulations conducted to generate a continuous output over the entire design space. With the surrogate model we could obtain a continuous map of vertical force and total power in the parametric space. The design space used a face centered cubic design with 15 design points and was complemented with 6 additional points, as shown in Table 3. Here we attempted to investigate the effects of three key parameters, i.e., the wing length, the mean chord length and the flapping frequency on aerodynamic force production and power output while stroke amplitudes and three angles of wing kinematics being remained unchanged as in Table 1. Note that the stroke amplitude and three angles as well as aspect ratio can also have impacts on force production and power consumption, which would lead to a complicated and time-consuming simulation process and thus were not accounted for but left for our future task.

With the case 1 (Table 3) as the basic case, we introduced a magnification factor for all the three design variables over a range from 0.75 to 1.25 (Fig. 3, Table 3), which resulted in a lower-and upper-limit in the three design variables as summarized in Table 4. Note that the lower and upper limits of the design variable space are unitized with the minimum of 0 and the maximum of 1.
Table 3  Design space comprising 21 cases

| Case | $c_m$ (mm) | $l$ (mm) | $f$ (Hz) |
|------|------------|----------|----------|
| 1(basic) | 10.82 | 32.55 | 140.00 |
| 2 | 13.52 | 32.55 | 140.00 |
| 3 | 8.11 | 32.55 | 140.00 |
| 4 | 10.82 | 40.69 | 140.00 |
| 5 | 10.82 | 24.41 | 140.00 |
| 6 | 10.82 | 32.55 | 175.00 |
| 7 | 10.82 | 32.55 | 105.00 |
| 8 | 13.52 | 40.69 | 175.00 |
| 9 | 8.11 | 40.69 | 175.00 |
| 10 | 13.52 | 24.41 | 175.00 |
| 11 | 13.52 | 40.69 | 105.00 |
| 12 | 8.11 | 24.41 | 175.00 |
| 13 | 8.11 | 40.69 | 105.00 |
| 14 | 13.52 | 24.41 | 105.00 |
| 15 | 8.11 | 24.41 | 105.00 |
| 16 | 8.11 | 32.55 | 105.00 |
| 17 | 8.11 | 24.41 | 140.00 |
| 18 | 10.82 | 24.41 | 175.00 |
| 19 | 10.82 | 40.69 | 105.00 |
| 20 | 13.52 | 40.69 | 140.00 |
| 21 | 13.52 | 32.55 | 175.00 |

Table 4  Upper-and lower-limits of three design variables and corresponding unitization

| Variables     | symbol | Upper Limit      | Unitized UL | Lower Limit    | Unitized LL |
|---------------|--------|------------------|-------------|----------------|-------------|
| mean chord length | $c_m$   | 13.52 mm         | 1           | 8.11 mm        | 0           |
| wing length    | $l$     | 40.69 mm         | 1           | 24.41 mm       | 0           |
| Flapping frequency | $f$     | 175.00 Hz        | 1           | 105.00 Hz      | 0           |

3 Results
3.1 Validation

The bioinspired dynamic flight simulator has been validated through a series of benchmark tests comprising self-consistency and comparisons in force-production between simulations and experimental measurements associated with flapping-wing flights in different species of insects in a wide range of Reynolds numbers (about $10^4$ to $10^5$) (Liu, et al., 1998; Liu, 2009; Liu and Aono, 2009). In this study, validation of the simulations was further carried out through a sensitivity analyses of grids and time step on time-varying vertical forces.

The body-fitted grid system includes a body-fitted grid around the insect body and two wing-fitted sub-grids around two wings embedded in the body-fitted grid (Liu, 2009). Two grid systems were employed including a coarse mesh with a body-fitted grid system of 38x38x38 and a background grid system of 54x54x54, and a fine mesh with 54x54x54 and 78x78x78, respectively. Furthermore, two steps of 0.001 and 0.0005 were tested for the time step effect. As shown in Fig. 4, the difference in both time-varying and period-average vertical force is a margin between the two grid systems and the two different time steps. Moreover, given the bumblebee with a total mass of 392.50mg, identical to a gravitational force on earth of 3.844mN, as shown in Table 1 (Kolomenskiy, et al., 2019), our simulation-based, period-averaged vertical force was obtained to be 3.885mN, which also validated the simulation in a manner of force integration. Therefore, we used the fine grid system and the smaller time step for all other simulations.
3.2 Aerodynamic forces and powers based on simulations and kriging model

Here we present the results of aerodynamics forces and powers based on the simulations and kriging model, which are summarized in Table 5 together with Reynolds numbers, reduced frequencies and Mach numbers. The kriging model excels polynomial response surface, radial basis neural network and support vector regressions; it can approximate the input points with less than 1\% error (Trizila, et al., 2008). As seen in Table 5 it is noted that the Mach numbers of several cases exceed 0.3, implying that the compressible effects may need to be taken into account for the cases, which is neglected in this study.

Figure 5 shows comparisons of time-varying vertical forces (Fig. 5 (a)), inertial and aerodynamic powers as well as total powers (Figs. 5 (b) – 5(d)) for cases that produce enough vertical force. The simulations for all the cases were conducted up to 4 beat cycles, reaching a stable stage with a completely periodic time course of forces and powers during the 4th beat cycle, and thus the results of the 4th beat cycle were used for all post-processing and analyses. As shown in Table 5, 10 of the 21 cases could produce an average vertical force greater than 1.46mN capable of achieving a hovering flight on Mars. With a significant increase in wing area and hence wing mass of the bumblebee models on Mars, the time-varying inertial powers as well as the total powers show an obvious increase in amplitudes (Figs. 5 (b) – 5 (d)) while keeping a low period-average value (Table 5). Note that the negative inertial power values are assumed to be utilized 100\%. It is an ideal assumption and will be discussed later. On the other hand, while having a much smaller amplitudes compared with those of inertial powers, the aerodynamics powers turn out to dominate the average total powers of the flapping flights on Mars.

Then we employed the most popular surrogate model – kriging model to build up a parameter space based on the wing length, the mean chord length, and the flapping frequency for vertical forces and total powers. The kriging model interpolates values based on a Gaussian process with respect to prior covariances. Given the simulation-based results of the 21 cases, the kriging model thereby composited a surrogate model on the average vertical forces and total powers over the entire parameter space \( \{u_c, u_f, u_l\} \), in which the design variables of \( u_c, u_f, u_l \) are unitized values varying between 0 and 1. Figure 6 illustrates the surrogate model-based results on 6 surfaces of the parameter space: vertical forces on lower and upper surfaces (Figs. 6(a) – 6(b)), and total powers on lower and upper surfaces (Figs. 6 (c) – 6 (d)). Figure 6 illustrates the period-average vertical forces and total powers in a parameter space (on 6 surfaces) based on kriging model. It is seen that the vertical force is most sensitive to wing length rather than flapping frequency and mean chord length (Figs. 6(a) - 6(b)) and a similar trend is also observed in Figs. 6 (c) – 6 (d).

Furthermore, we plotted an iso-potential surface associated with a vertical force of 1.46mN in the parameter space in Fig. 7. In order to explore the optimal design point with the power output minimized, we then colored the surface with the average total power required. Substantially the minimum total power was found corresponding to a set of unitized variables of \( u_c, u_f, u_l = (0.87, 0.75, 0.00) \) by searching the whole data set throughout the iso-surfaces for minimum value, and was marked accordingly depicted in Fig. 7. For this specific case, we carried out an additional simulation, yielding a vertical force of 1.4626mN and a total power of 0.0509W. This optimal case corresponds with a set of design variables, \( c_m, l, f \) to be 3.13, 2.46 and 0.77 times of those in the original bumblebee model on earth, respectively. Note that the Mach number for the optimal case is 0.24, indicating that the incompressibility assumption holds for the case.
Fig. 5 Comparisons of (a) time-varying vertical forces, (b) inertial powers, (c) aerodynamic powers and (d) total powers.
Table 5  Period-average vertical force, inertial and aerodynamic powers, Reynolds number, reduced frequency and Mach number

| Case | $F_z$ [mN] | $P_{iner}$ [W] | $P_{aero}$ [W] | $P_{total}$ [W] | $R_e$ | $k$ | $Ma$ |
|------|------------|----------------|----------------|-----------------|-------|----|-----|
| 1    | 1.4788     | 0.0036         | 0.0589         | 0.0626          | 254.5512 | 0.2146 | 0.2845 |
| 2    | 1.8672     | 0.0048         | 0.0763         | 0.0811          | 318.1890 | 0.2683 | 0.2845 |
| 3    | 1.0932     | 0.0026         | 0.0430         | 0.0456          | 190.9134 | 0.1610 | 0.2845 |
| 4    | 2.9100     | 0.0034         | 0.1422         | 0.1456          | 318.1890 | 0.1717 | 0.3556 |
| 5    | 0.5994     | 0.0017         | 0.0197         | 0.0213          | 190.9134 | 0.2862 | 0.2134 |
| 6    | 2.3364     | 0.0071         | 0.1153         | 0.1224          | 318.1890 | 0.2146 | 0.3556 |
| 7    | 0.8180     | 0.0008         | 0.0248         | 0.0256          | 190.9134 | 0.2146 | 0.2134 |
| 8    | 5.8134     | 0.0172         | 0.3524         | 0.3696          | 497.1703 | 0.2146 | 0.4445 |
| 9    | 3.2449     | 0.0096         | 0.1943         | 0.2039          | 298.3022 | 0.1288 | 0.4445 |
| 10   | 1.1784     | 0.0044         | 0.0501         | 0.0545          | 298.3022 | 0.3577 | 0.2667 |
| 11   | 2.0957     | 0.0037         | 0.0783         | 0.0820          | 298.3022 | 0.2146 | 0.2667 |
| 12   | 0.7140     | 0.0023         | 0.0276         | 0.0298          | 178.9813 | 0.2146 | 0.2667 |
| 13   | 1.2065     | 0.0021         | 0.0441         | 0.0462          | 178.9813 | 0.1288 | 0.2667 |
| 14   | 0.4042     | 0.0010         | 0.0112         | 0.0121          | 178.9813 | 0.3577 | 0.1600 |
| 15   | 0.2520     | 0.0005         | 0.0061         | 0.0066          | 107.3888 | 0.2146 | 0.1600 |
| 16   | 0.6174     | 0.0011         | 0.0180         | 0.0191          | 143.1851 | 0.1610 | 0.2134 |
| 17   | 0.4491     | 0.0006         | 0.0141         | 0.0147          | 143.1851 | 0.2146 | 0.2134 |
| 18   | 0.9531     | 0.0032         | 0.0384         | 0.0416          | 238.6418 | 0.2862 | 0.2667 |
| 19   | 1.6746     | 0.0029         | 0.0610         | 0.0639          | 238.6418 | 0.1717 | 0.2667 |
| 20   | 3.6882     | 0.0044         | 0.1795         | 0.1839          | 397.7363 | 0.2146 | 0.3556 |
| 21   | 2.9578     | 0.0093         | 0.1494         | 0.1588          | 397.7363 | 0.2683 | 0.3556 |

Note that the inertial power shows a period-averaged value close to 0 while having a large-amplitude fluctuation at up- and down-stroke (Figs. 5 (b) - 5 (d)). The positive part (Fig. 5 (b), power curve above 0) is taken into account for evaluating time-average power in Fig. 8 whereas the negative part (Fig. 5 (b), power curve below 0) is assumed to be 100% utilized in terms of time-average power in Fig. 8. However, it is not realistic to assume the negative power being 100% utilized because of power loss and the rate of power conversion should be taken into account. As seen in Table 6, the total power shows a steep decrease with increasing the inertial power utilized over a range of 0% up to 100%. Clearly the negative power utilized can be an important issue, which will be extensively studied in the future.

(a) vertical force, lower faces  
(b) vertical force, upper faces
Fig. 6 Period-average vertical forces and total powers in a parameter space based on kriging model. Period-average vertical forces on 6 surfaces with unitized variables of (a) $u_c = 0$, $u_f = 0$, and $u_l = 0$; (b) $u_c = 1$, $u_f = 1$, and $u_l = 1$. Period-average powers on 6 surfaces of (c) $u_c = 0$, $u_f = 0$, and $u_l = 0$; (d) $u_c = 1$, $u_f = 1$, and $u_l = 1$. Note that the design variables $u_c$, $u_f$, $u_l$ are unitized values varying between 0 and 1.

Fig. 7 Iso-potential surface of vertical forces with a value of 1.46 mN, colored with respect to average total powers required. The optimal point where the power requirement is lowest is marked as a red filled circle.

Fig. 8 Negative powers and corresponding total powers.
4. Discussion

4.1 Bumblebee-inspired flapping-wing aerodynamics on earth and Mars

To explore the effects of low Martian air density on flapping-wing aerodynamics, we made a comparison between the two bumblebee-inspired models on earth (original bumblebee model in Table 1, Fig. 2) and Mars (the basic case 1 in Table 3, Figs. 2-3). Here the Reynolds number and reduced frequency associated with the earth model were 2748 and 0.1742, respectively. Note that the bumblebee-inspired model on Mars is correspondent to a much lower Reynolds number of approximately 254, sharing the same order of fruit fly hovering on earth but with the reduced frequency of 0.2146 changed slightly.

Figure 8 shows a comparison among the time-varying vertical forces of the bumblebee-inspired model on Mars, the original bumblebee model on earth, and the original bumblebee model on earth with the bumblebee kinematic model on Mars. The curve for the case of default wing on Mars is oscillating because of grid settings remain the same as that on Earth, but the features of the upstroke and downstroke are similar to that of default wing on Earth, only with the magnitude scaling down. Apparently while the original bumblebee model merely generates a marginal vertical force on Mars due to the much lower atmospheric density, the bumblebee-inspired model on Mars with the enlarged wing (the basic case 1) does produce enough vertical force. Furthermore, the low Reynolds number on Mars owing to the much larger kinematic viscosity of $9.42\times10^{-5}\text{m}^2/\text{s}$ compared with that of $1.593\times10^{-5}\text{m}^2/\text{s}$ on earth obviously leads to a marked reduction in the vertical forces by the original bumblebee model on earth. This implies that the key discrepancy between the flapping-wing aerodynamics on earth and Mars is likely due to the Reynolds number effects: the bumblebee-inspired model on Mars can achieve hovering flights but in a much lower Reynolds number regime. This is supported by the visualized iso-speed surfaces about the bumblebee-inspired models in hovering flights on earth and Mars in a complete beat cycle (Fig. 10).

Although the flow structures share the similar vortex-based features in terms of leading-edge vortex, trailing-edge vortex and wing tip vortex, the vortex dynamics associated with the bumblebee-inspired model on Mars is characterized by low velocities and stable leading-edge vortices. This result is also supported by our previous study on the size effects of flapping aerodynamics on insect hovering (Liu, et al., 2009), in which, the leading-edge vortices and tip vortices in fruit fly hovering at a Reynolds number of 134 are observed stable without breaking down throughout the half strokes.
Fig. 10 Iso-vorticity surfaces (vorticity magnitude = 3/s) colored by speed-magnitude about bumblebee-inspired models in hovering flight (perspective front-view) on (a) Earth and (b) Mars at pronation (t/T = 3.0, the end of upstroke and the beginning of downstroke), mid-downstroke (t/T = 3.2, downstroke), and mid-upstroke (t/T = 3.7, upstroke). The magnitudes on the colorbars have a velocity-dimension, m/s.

4.2 Association between vertical force and design variables

Given the specific relationship between the vertical force and the three design variables in Eq. (6) we further explore some scaling law which is expected capable of reasonably and simply predicting the vertical forces in the parameter space of the wing length, the mean chord length, and the flapping frequency. According to Eq. (6), given the low Reynolds number regime (Table 5), with stroke amplitude and air density fixed, it would be reasonable to assume that the vertical force coefficient $C_{Fz}$ could be kept unchanged and for instance, defined with the results of basic case 1, then the vertical forces in the whole parameter space could be predicted with the specific relation of $Fz \sim C_{Fz} f^2 l^3$.

Table 6 shows a comparison of vertical force and total power between the Eq. (6)-based estimation and the CFD simulations. Note that several cases show larger errors, for instance, cases 9, 10, 14, 18, implying that the scaling law could not make reasonable prediction for these specific cases. These cases however are far away from the original case in the parameter space. Obviously, for all the feasible design points with the vertical force greater than 1.46mN, the specific relation can provide a reasonable prediction on both vertical force and total power with the maximum errors less than 5% and 10%, respectively (Table 6). Validity of the assumption on the unchanged vertical force coefficients, $C_{Fz}$, was further confirmed by a comparison of CFD-based vertical force coefficients among all the 21 cases. As illustrated in Fig. 11, all vertical force coefficients where the cases produce enough vertical forces drop within a narrow band with slight differences while showing the same time-varying feature. This indicates that Eq. (6) can be a good approximate to the prediction of vertical force and thus an effective way to seek optimal design points based on the surrogate model. Bluman (Bluman, et al., 2018) developed a scaled-up flapping-wing model with a ratio of 3.5 for Mar
surface rovers and reported a minimum power requirement of 188W/kg, which is identical to a total power output of approximately 0.0752W, in reasonable consistent with that (0.0626W) of the basic case in the present study. However, since the present scaling law is merely viable to the limited cases, it should be pointed out that the scaling law could only be a primary approximation and further investigations are required in the future.

Table 6 Comparison of vertical forces and total powers between a specific relation $F_z \sim c m f^2 l^3$ and CFD simulation

| Case | $F_z$[mN] (CFD) | $P_{total}$[W] (CFD) | $F_z$[mN] (scaling) | $P_{total}$[W] (scaling) | Error of vertical force | Error of Power |
|------|----------------|----------------------|---------------------|------------------------|------------------------|----------------|
| 1    | 1.4788         | 0.0626               | 1.4788              | 0.0626                 | 0.00%                  | 0.00%          |
| 2    | 1.8672         | 0.0811               | 1.8485              | 0.0782                 | -1.00%                 | -3.51%         |
| 3    | 1.0932         | 0.0456               | 1.1091              | 0.0469                 | 1.45%                  | 2.98%          |
| 4    | 2.9100         | 0.1456               | 2.8883              | 0.1528                 | -0.75%                 | 4.95%          |
| 5    | 0.5994         | 0.0213               | 0.6239              | 0.0198                 | 4.08%                  | -7.23%         |
| 6    | 2.3364         | 0.1224               | 2.3106              | 0.1222                 | -1.10%                 | -0.12%         |
| 7    | 0.8180         | 0.0256               | 0.8318              | 0.0264                 | 1.69%                  | 3.20%          |
| 8    | 5.8134         | 0.3696               | 5.6412              | 0.3730                 | -2.96%                 | 0.90%          |
| 9    | 3.2449         | 0.2039               | 3.3847              | 0.2238                 | 4.31%                  | 9.73%          |
| 10   | 1.1784         | 0.0545               | 1.2185              | 0.0483                 | 3.41%                  | -11.25%        |
| 11   | 2.0957         | 0.0820               | 2.0308              | 0.0806                 | -3.10%                 | -1.80%         |
| 12   | 0.7140         | 0.0298               | 0.7311              | 0.0290                 | 2.40%                  | -2.76%         |
| 13   | 1.2065         | 0.0462               | 1.2185              | 0.0483                 | 0.99%                  | 4.60%          |
| 14   | 0.4042         | 0.0121               | 0.4387              | 0.0104                 | 8.53%                  | -13.83%        |
| 15   | 0.2520         | 0.0066               | 0.2632              | 0.0063                 | 4.45%                  | -5.37%         |
| 16   | 0.6174         | 0.0191               | 0.6239              | 0.0198                 | 1.05%                  | 3.48%          |
| 17   | 0.4491         | 0.0147               | 0.4679              | 0.0148                 | 4.19%                  | 1.24%          |
| 18   | 0.9531         | 0.0416               | 0.9748              | 0.0387                 | 2.28%                  | -7.14%         |
| 19   | 1.6746         | 0.0638               | 1.6247              | 0.0644                 | -2.98%                 | 0.94%          |
| 20   | 3.6882         | 0.1839               | 3.6104              | 0.1910                 | -2.11%                 | 3.83%          |
| 21   | 2.9578         | 0.1588               | 2.8883              | 0.1528                 | -2.35%                 | -3.78%         |

Fig. 11 Comparison of vertical force coefficients among different cases.

5. Conclusions

In this study we have developed an integrated computational model for exploring a power-efficient flapping-wing design for Mars surface rovers by combing a surrogate model and CFD simulations in a three-variable parametric space involving the wing length, the mean chord length, and the flapping frequency. Our results indicate that the strategy of enlarging the wing configuration of a bumblebee can be a feasible way to achieve a hovering flight on Mars with
multiple solutions, which leads to a minimum power output of 0.0509W. This study therein provides a novel and feasible bumblebee-inspired flapping-wing design for hovering flight on Mars. Moreover, a scaling law associating the vertical force with the three variables is found to be capable of reasonably and simply predicting the vertical forces by a specific relation of $F_z \sim c m f^2 l^3$.

On the other hand, there does exist a big gap between the present design and the realistic development of flapping-wing MAV design for Mars surface rovers. The optimal design point achieved here is a primary one limited in a specific parametric space whereas the morphological and kinematic effects of flapping wings on hovering aerodynamic force production and power consumption on Mars needs to be further explored in a broader parametric space. Compressible effects also need to be accounted for at larger Mach numbers exceeding 0.3. Despite the limitations, the methodology established in the present study can be further applied to explore capabilities of other insect-inspired flapping-wing designs for Mars surface rovers in terms of different insect species including fruit fly, hawkmoth, butterfly, etc. as well as other parameters of aspect ratio, stroke amplitude and three angles of wing kinematics.

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