Data-driven CFD Scaling of Bioinspired Mars Flight Vehicles for Hover

Jeremy A. Pohly¹, Chang-kwon Kang¹, D. Brian Landrum¹, James E. Bluman², Hikaru Aono³
¹University of Alabama in Huntsville, Huntsville, AL 35899
²United States Military Academy, West Point, NY 10996
³Shinshu University, Tokida, Ueda, Nagano, Japan

Abstract

One way to improve our model of Mars is through aerial sampling and surveillance, which could provide information to augment the observations made by ground-based exploration and satellite imagery. Flight in the challenging ultra-low-density Martian environment can be achieved with properly scaled bioinspired flapping wing vehicle configurations that utilize the same high lift producing mechanisms that are employed by insects on Earth. Through dynamic scaling of wings and kinematics, we investigate the ability to generate solutions for a broad range of flapping wing flight vehicles masses ranging from insects $\mathcal{O}(10^{-3})$ kg to the Mars helicopter Ingenuity $\mathcal{O}(10^{0})$ kg. A scaling method based on a neural-network trained on 3D Navier-Stokes solutions is proposed to determine approximate wing size and kinematic values that generate bioinspired hover solutions. We demonstrate that a family of solutions exists for designs that range from 1 to 1000 grams, which are verified and examined using a 3D Navier-Stokes solver. Our results reveal that unsteady lift enhancement mechanisms, such as delayed stall and rotational lift, are present in the bioinspired solutions for the scaled vehicles hovering in Martian conditions. These hovering vehicles exhibit payloads of up to 1 kg and flight times on the order of 100 minutes when considering the respective limiting cases of the vehicle mass being comprised entirely of payload or entirely of a battery and neglecting any transmission inefficiencies. This method can help to develop a range of Martian flying vehicle designs with mission viable payloads, range, and endurance.

Keywords

Mars flight vehicle concept; Mars exploration; Bioinspired unsteady aerodynamics; Flapping wing

---

This manuscript version is made available under the CC-BY-NC-ND 4.0 license https://creativecommons.org/licenses/by-nc-nd/4.0/

Declaration of Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.
1 Introduction

Improved information about the Martian environment will reduce uncertainties and risks in future exploration, including human missions. Aerial vehicles can perform sensing and other tasks that fill the gaps in the information gathering capabilities of Mars orbiters and land-based rovers. Flight vehicles capable of near-surface hovering are attractive candidates for such information gathering missions. These missions may include surveying remote locations, retrieving samples, efficiently generating topographic models of the surrounding terrain, providing near-surface weather data, and assisting rovers in path planning. In addition, the recent advancements in swarming flight and autonomy offer additional design options and possibly improved efficiencies for these missions [1].

Though the atmospheric viscosity on Mars is similar to that of Earth, \( \mu_{\text{Mars}} = 0.83 \mu_{\text{Earth}} \) [2], the ultra-low density atmospheric environment has proved a difficult challenge in designing realizable Martian flight vehicles. Despite the gravitational acceleration on Mars requiring less lift production than on Earth for a given vehicle mass, where \( g_{\text{Mars}} = 0.38 g_{\text{Earth}} \), the reduced density on Mars compared to Earth being \( \rho_{\text{Mars}} = 0.0142 \rho_{\text{Earth}} \) can be quite prohibitive for generating sufficient aerodynamic forces to fly using conventional designs [3]. Although NASA is sending the helicopter Ingenuity to Mars during the 2020 Perseverance rover mission, such a solution results in a design that is relatively large (around 1.8 kg vehicle with a 1.21 m rotor diameter) [4] and potentially less aerodynamically efficient when operated at the low Reynolds numbers inherent to Martian flight [5].

Bioinspired flapping wing solutions can overcome the difficulties associated with flight in the rarefied Martian atmosphere [6]. The thin Martian atmosphere results in a relatively low Reynolds number \( Re \) which is directly proportional to the fluid density \( \rho \). Insects make use of efficient, unsteady aerodynamic mechanisms that occur at low Reynolds numbers. These mechanisms include delayed stall via an attached leading-edge vortex, wake capture, and enhanced circulation via rotational lift [7,8]. As such, properly scaled flapping wing motion on Mars has been demonstrated to exhibit the same mechanisms and potential for flight [6,9].

The method used to achieve these bioinspired solutions on Mars is based on the well-established fluid dynamics concept of dynamic similarity [10,11]. In general, to dynamically scale a system in the context of fluid dynamics is to preserve the geometrical shape but change the relevant dimensional parameters (e.g. fluid density, viscosity, wing velocity, etc.) such that the set of governing dimensionless parameters (e.g. Reynolds number, lift coefficient, etc.) is preserved between the two configurations. For example, dynamic similarity guides the scaling of model aircraft for sub-scale wind tunnel tests before full-scale flight tests are performed. Not only does dynamic similarity allow for convenient physical scaling of the system, it also reduces the total number of parameters required to fully describe a system involving multiple parameters, thus reducing the design space to a more manageable set of parameters [12].

Our previous bioinspired solutions [6] are dynamically similar to terrestrial insects’ flapping wing motions, and take advantage of similar unsteady, high lift coefficient producing
mechanisms on Mars. The relevant set of dimensionless parameters for a rigid flapping wing are: aspect ratio \( AR \), related to the slenderness of a wing; Reynolds number \( Re \), the ratio between the flow inertia and viscous forces; reduced frequency \( k \), a measure of flow unsteadiness; Mach number \( M \), related to the flow compressibility; and pitch amplitude \( A \), measuring the wing’s angle of attack. To maintain dynamic similarity with insects on Earth, these parameters were kept in the insect-inspired flight regime. Starting from the morphological parameters corresponding to a bumblebee, the wings were uniformly scaled to approximately the size of cicada wings. The flapping frequency was also reduced to 63 Hz, approximately 43% that of a bumblebee (~155 Hz). Generating such a solution through biomimicry not only provides a means of producing sufficient lift, but it also results in a flight vehicle that has the potential to benefit from other attractive qualities of insect flight such as hovering, high maneuverability, long range/endurance flight, and high payload capacity. To exploit the advantages of insect-inspired flight, we extended the study to quantify the payload margin of the bumblebee-inspired flapping wing micro air vehicle (FWMAV) and determined that it can carry a payload on the order of its own body weight [13]. It was determined that the payload capabilities are limited by maintaining dynamically similar motion.

While successful flapping wing flight on Mars has been simulated [6,9], these results were limited to vehicle masses that were less than 1 gram, operated at Reynolds numbers of less than 200, and reduced frequencies between 0.2 and 0.35. The general scaling range between viable insect-inspired flapping wing vehicles and infeasible designs is currently unknown. This paper seeks to identify the physical solution range for bioinspired flapping wing flight on Mars. We present a data-driven CFD scaling model that accounts for nonlinearities in the mean lift based on the relevant dimensionless parameters. Using this method, we generate hover solutions for flapping wing vehicles on Mars that range from 1 gram to 1 kilogram. We verify these bioinspired solutions using a well-validated 3D Navier-Stokes equation solver. Furthermore, we investigate the resulting dimensional design space to understand the trends and limits of scaling a bioinspired flapping wing vehicle for flight on Mars. Our previous solution at the insect scale [13] had a mass of 0.2 grams. Current Earth-based flapping wing robots have masses of \( O(10^0 - 10^1) \) grams. These include Chiba University’s bioinspired MAV (6 grams) [14], the DelFly II (16 grams) [15], the Nano Hummingbird (19 grams) [16], the KUBeele-S (16 grams) [17,18], and various other FWMAV prototypes (6 and 12 grams) [19]. Additionally, the Mars helicopter Ingenenuity mass is \( O(10^3) \) grams [4]. While insect size micro-air vehicles can employ stealth, larger vehicles with increased payload capability can be more beneficial for Mars exploration since they can carry larger sensors than insect-size vehicles. We provide a method for generating dynamically similar hovering design solutions for Martian flapping wing robots with total masses on the order of the current Earth FWMAVs, as well as the Mars helicopter Ingenenuity.

2 Methodology

The approach to finding a bioinspired solution builds on methodology from our past studies [6,13]. We originally used a trimming algorithm to modify the kinematics such that the lift balances the weight in dynamical equilibrium. Here we develop a general methodology to

Acta Astronaut. Author manuscript; available in PMC 2022 March 01.
scale the wing size and kinematics to achieve a lift force that balances the vehicle weight on Mars in an averaged sense. We first determine a dynamically similar solution based on the desired vehicle mass by using a scaling method (Section 2.4). This scaling method leverages the results from a CFD design space study across a range of dimensionless parameters to combine the relevant dimensionless parameters for maintaining dynamic similarity with the lift-weight balance given by

\[ 2\langle L \rangle = W = mg = \rho U_{\text{ref}}^2 S C_L. \]  

(1)

Here, \( \langle L \rangle \) is the mean aerodynamic lift force of one wing, \( W \) is the vehicle weight on Mars, \( m \) is the vehicle mass, \( g \) and \( \rho \) are the gravitational acceleration and atmospheric density on Mars, respectively, \( U_{\text{ref}} \) is the reference velocity of a flapping wing, \( S \) is the planform area of a single wing, and \( \langle C_L \rangle \) is the mean lift coefficient. For the mean values of time dependent quantities, such as \( L(t) \), \( C_L(t) \), and later \( P(t) \) (power), we consider the integrated value of the first two flapping periods as

\[ \langle X \rangle = \frac{1}{2T} \int_0^{2T} X(t) dt, \]  

(2)

where \( X(t) \) is the time dependent quantity to average, \( t \) is the time, and \( T \) is a flapping period. We assume that there are two wings on the vehicle. We then use a well-validated, three dimensional Navier-Stokes (NS) equation solver \([20,21]\) to determine the forces for hovering flight of our insect-inspired flapping wing flyer.

2.1 Design Framework

Our design framework consists of a single, quarter-elliptic wing which performs insect-like flapping and pitching motion (Fig. 1). The wing is characterized primarily by the chord distribution \( c(y) \), the single-wing span \( R \), and the spanwise location of the center of second moment of area \( R^2 \) (see Sections 2.2 and 2.4 for full a definition of wing parameters). We only consider the aerodynamics of the vehicle’s single wing and make no consideration for the actuator dynamics, vehicle structures, or their imposed masses on the system. Although these components and the scaling of their associated mass penalties are critical parts of the overall system design and minimization of the vehicle mass, we seek to only address the vehicle’s aerodynamic scaling and the resulting power required. We do not solve the multibody dynamic equations of motion for the flapping wing vehicle. We instead consider the forces produced by a single flapping wing fixed to an inertial frame (subscript I in Fig. 1b), only simulating the case of rigid wings, which has been shown to elucidate a multitude of phenomena for flapping wing simulations \([8,21,22]\). The power required for the flapping motion in hover is calculated based on the resulting inertial and aerodynamics forces and moments for rigid and idealized flexible wings (see Section 3.4 for a detailed definition and discussion).

Flapping wing flight is characterized by unsteady flow with large vortical structures. To properly account for the unsteady lift enhancing mechanisms, the generation of large
scale vortices [24] and their nonlinear interaction with the wing [25,26] must be properly resolved by solving the NS equations. Although there has been success in developing high-fidelity quasi-steady aerodynamics models for flapping wing motion [27-29], these models are less accurate when more extreme kinematics and dimensionless parameters are considered [30]. Therefore, our computational framework utilizes the benefits of solving the 3D incompressible NS equations to calculate the velocity and pressure field around the flapping wing in a low Re flow regime. NS equations are solved numerically using an in-house three-dimensional, structured, pressure-based, finite volume solver [20,31,32]. The equations are solved in an inertial frame of reference, such that the body-fitted mesh rotates rigidly with the wing. The computational setup as well as grid and time step sensitivity studies can be found in Appendix 1. Validation of solving the 3D NS equations for a single flapping wing can be found in Appendix 2.

2.2 Wing kinematics and geometry

The wing kinematics are described using bioinspired relations [33], focusing on the flapping and pitching motion, while ignoring deviation motion for a simplified design space. The flapping motion is represented by the flapping angle $\phi$ with respect to the wing root, and is defined as the harmonic motion

$$\phi(t / T) = \frac{\Phi}{\arcsin(\kappa)} \arcsin[\kappa \cos(2\pi ft)],$$

(3)

where $\Phi$ is the flapping amplitude, and the time $t$ is normalized by the period $T = 1/f$. The parameter $\kappa$ is used to convert the flapping motion from a purely triangular profile ($\kappa = 1$) to a sinusoidal profile ($\kappa \rightarrow 0$). Although sinusoidal flapping is an abstraction of insect motion, this constraint reduces the overall design space. For all cases considered in this study $\kappa = 0.01$, resulting in a nearly sinusoidal flapping profile (Fig. 2). The pitching motion $\alpha$ is described by

$$\alpha(t / T) = \frac{A}{\tanh(\delta)} \tanh[\delta \sin(2\pi ft)],$$

(4)

where $A$ is the pitch amplitude, and $\delta$ is a parameter used to convert the pitching motion from a purely square wave ($\delta \rightarrow \infty$) to sinusoidal ($\delta \rightarrow 0$). For all cases considered in this study, $\delta = 2.0$, resulting in a modified square wave (Fig. 2), which is consistent with other studies [6,27,34]. The combination of sinusoidal flapping and modified square pitching profiles can lead to enhanced effectiveness of the lift generated [35].

Both the pitching and flapping motions are harmonic, with a 90 degree phase difference. Additionally, the motions are symmetric, with no difference between the upstroke and downstroke. While the flapping amplitude $\Phi$ can vary due to the scaling method presented in Section 2.4, we fix the pitch amplitude at $A = 45^\circ$ to achieve maximum lift [28,29]. The instantaneous pitch angle $\alpha(t)$ is a function of time varying between $-A \leq \alpha(t) \leq A$. Placing the pitch axis at the leading edge emulates that of most current flapping wing air vehicles [14,23].
The wing geometry is defined by a quarter-elliptic chord distribution of a thin wing. Because the biological and bioinspired wings are thin, operating at relatively high angles of attack, the exact shape of the airfoil plays a relatively less important role than for passenger airplanes. One of the main reasons is that the LEVs, which characterize bioinspired flight, form from the thin leading edge [36]. That said, twist [37] and camber (active or passive) [38] can influence the resulting aerodynamics, although we do not model these effects. The only geometric wing parameter that we vary is the aspect ratio $AR$. Although we do not vary the wing planform, it has been shown that there exist optimal planform shapes with respect to aerodynamic power required for flapping wings [39] and that wing size can affect the stability and attachment of the high lift producing leading edge vortex and the resulting power factor [40-43].

This leads to the fact that there is a wide range of variables and parameters that govern flapping wing flight that could result in a potential decrease in or optimization of power. In addition to the wing shape effects mentioned previously, kinematic parameters that govern the waveform of the pitching and flapping motion [35], the timing of wing rotations [33], the inclusion of deviation in the wing motion [33], pitch axis location [30,44], etc. can enhance the lift generation or reduce power. Similarly, variation of the pitch amplitude can generate more efficient lift-to-drag ratios and power factors [35]. While we acknowledge the improvements that can be achieved with variations in these parameters, we do not model these effects as we are not seeking an optimal solution in this study. Rather, we seek to understand the general trends that the relevant dimensionless parameters exhibit for obtaining scaled solutions for hover flight on Mars. No cost functions, such as lift or power, have been considered in the formulation of the scaling method. Minimization of power required in the Martian atmospheric conditions can be investigated further by varying wing size and motion, as considered by other researchers [9].

### 2.3 Aerodynamic modeling

We assume any aerodynamic forces generated by the body in hover can be neglected [45]. We simulate a single, rigid wing assuming left-right symmetry of the system with respect to the longitudinal plane. We directly solve the three-dimensional incompressible NS equations given by

\[
\nabla^* \cdot \vec{V}^* = 0,
\]

\[
\frac{k}{\pi} \frac{\partial \vec{V}^*}{\partial \tau} + (\vec{V}^* \cdot \nabla^*) \vec{V}^* = -\nabla^* p^* + \frac{1}{Re} \nabla^* \cdot (\nabla^* \vec{V}^*)
\]

Equation (5)

to determine the pressure and shear stress on the wing. The velocity field $\vec{V}$ is normalized with the reference velocity $\vec{V}^* = \vec{V} / U_{ref}$ (Section 2.4). As with the kinematics, time is normalized by the flapping period $\tau = fT$ with $T = 1/f$. Lengths are normalized by the mean wing chord $c$, and pressure is normalized per $p^* = p / \rho U_{ref}^2$. The reduced frequency $k = \pi f c U_{ref}$ appears as a dimensionless scaling constant. These equations are solved using a well-validated structured, finite-volume, pressure-based incompressible NS equation solver.
used extensively in flapping wing studies [20,21]. For all simulations considered in this study, the resulting Reynolds number is in the range of $Re < 12,000$. The fluid flow in this Reynolds number regime can be considered as laminar and the computational accuracy of the NS equation solver employed in this study is satisfactory [46].

Note that we do not investigate the effects of the blade Lock number, which is the ratio of aerodynamic to inertial forces acting on the flapping wing. Although this dimensionless parameter may become important to both the vehicle structural and flight dynamics, as in the case of Ingenuity [47], we do not model the structural or multi-body dynamics of the vehicles in the present work. However, we do discuss and report the inertial and aerodynamic components of power and their relative differences for various sized flapping wing vehicles on Mars (see Section 3.4).

### 2.4 Scaling method for dynamically similar solutions

The proposed method seeks to ensure that the resulting body parameters and motion are dynamically similar to insects on Earth [6,48] and can therefore benefit from the high lift mechanisms typical of unsteady insect motion. Insect lift coefficients with rigid wings are governed by five dimensionless parameters [8,32] such that

$$C_L = C_L(AR, k, Re, A, M).$$

These parameters are defined by combinations of morphological and kinematic parameters as shown in Table 1. In Table 1, $R$ is the span of one wing (Fig. 1a), $S$ is the planform area of one wing, $f$ is the flapping frequency, $c$ is the mean chord length, $\Phi$ is the half peak-to-peak flapping amplitude, and $U_{ref} = 2\pi f \Phi R^2$ is the average reference velocity of the wing. It is evaluated at the spanwise location of the center of the second moment of area of the wing (about the flapping axis). This location is denoted as $R_2 = \hat{R}_2$, where $\hat{R}_2$ is the dimensionless location of the center of the second moment of area. Note that $R_2$ is a point on the wing (see Fig. 1a) whose velocity has been shown to capture the overall velocity of the wing in an averaged sense and therefore, the parameters that are calculated at this location such as Reynolds number accurately represent the flapping wing aerodynamics [8,29]. Additionally, $l_{ref}$ is a reference length chosen such that $l_{ref} = c$, $\nu$ is the kinematic viscosity of the fluid, and $a$ is the speed of sound in the Martian atmosphere. Using the ranges provided in Table 1 and the physical parameters defined in Fig. 1 for the FWMAV, a range of solutions with resulting dimensionless parameters in the insect regime can be determined for a given vehicle mass.

#### 2.4.1 Data-driven CFD model for predicting mean lift coefficient using a neural-network

In order to formulate a method for scaling the wing parameters for flapping wing flight on Mars, we seek solutions that operate within the bounds of the dimensionless parameters governing insect flight (see Table 1). We input the vehicle mass $m$, wing aspect ratio $AR$, and desired reduced frequency $k$ in order to output the wing size ($S$, $c$, and $R$), along with the required kinematics ($f$ and $\Phi$). The relations between geometric and kinematic dimensionless parameters with respect to the physical...
parameters are algebraic. The main challenge is the nonlinear relation between the primary dimensionless parameter $\langle C_L \rangle$ and other parameters, given by Eq. (1).

In order to understand the impact that the relevant dimensionless parameters have on the mean lift coefficient, we use a data-driven CFD model using the Navier-Stokes equation-based insect flight simulator (Section 2.3) in a training design space of $(AR, k, \text{and } Re)$ at $A = 45^\circ$ and $M_{tip} = 0.1$. A total of 125 Navier-Stokes equation solutions were calculated that swept the dimensionless parameter space as described in Table 2.

The effects of Mach number and pitching angle were not included in this training design space. This is due to the observations that insects fly well within the incompressible flow regime (Table 2). Additionally, the pitch amplitude of the wing was fixed at 45° (see discussion in Section 2.2). As noted previously (Fig. 2), all simulations are run with a modified square-wave pitching profile ($\delta = 2.0$) and sinusoidal flapping profile ($\kappa = 0.01$).

Of the 125 CFD resultant simulations, a random set of 100 training simulations was used to train a neural network model via TensorFlow in combination with the neural-network library Keras in Python. Because solving for $\langle C_L \rangle$ as a function of $AR, k, \text{and } Re$ is a nonlinear regression problem, we selected a sequential model with two densely connected, 64-unit hidden layers in addition to an output layer that returns a single continuous value for $\langle C_L \rangle_{\text{NN}}$—the mean lift value returned from the neural-network model. Using 3 inputs units, 128 hidden-layer units (2×64), and 1 output unit resulted in 4481 trainable parameters (weights) with which to optimize the model (Fig. 3a). The results comparing the predicted $\langle C_L \rangle_{\text{NN}}$ to the true $\langle C_L \rangle_{\text{NS}}$ from the NS simulations can be found in Fig. 3b. Note that the model performs well at predicting the mean lift coefficient for the remaining 25 test cases which were not used in training the model. The percent difference for the model, given as

$$\langle C_L \rangle_{\text{diff}} = \frac{1}{\langle C_L \rangle_{\text{NS}}} \left| \langle C_L \rangle_{\text{NS}} - \langle C_L \rangle_{\text{NN}} \right| \times 100,$$

is used to determine a maximum difference of 8.8%, a minimum of 0.14% and a mean value of 2.5%. This demonstrates that the data-driven neural-network model $\langle C_L \rangle_{\text{NN}}$ can be reasonably used to predict the mean lift coefficient under the assumption of the fixed pitching kinematics, wing geometry, and ranges of dimensionless parameters considered in Table 2. Although increases in the number of trainable parameters, training simulations, and test simulations can likely increase the predictive capabilities of the neural network model, the results generated by the model presented in this study satisfactorily predict the lift coefficient for our scaling purposes (see Fig. 6 in Section 3.2).

### 2.4.2 Bioinspired scaling method

Obtaining a dynamically similar solution is non-trivial as there are multiple dimensionless parameters with nonlinear relationships between these parameters. Also, a small change in one parameter can quickly drive another parameter out of the insect-inspired regime. Furthermore, calculation of the lift coefficient $\langle C_L \rangle$ requires a known value of the Reynolds number, e.g. Eq. (1). However, the Reynolds number depends on the wing size, which is to be determined from the solution.
The proposed scaling method inputs the desired mass of the vehicle $m$ along with desired values for $AR$ and $k$. The output variables are the dynamically similar solutions in terms of the flapping frequency $f$ and amplitude $\Phi$, and the wingspan $R$ and mean chord $c$, required to balance the weight of the desired vehicle on Mars (as discussed at the beginning of Section 2. Thus, this scaling method generates a baseline design for the physical characteristics of a flapping wing vehicle with a target mass. A summary of the method can be found in Fig. 4, and the details for each step can be found below.

**Step 1. Define maximum wing velocity:**

The first constraint imposed by dynamically similar motion on Mars is the effect of the Mach number $M$ on the reference velocity $U_{ref}$. When compared with the same velocity on Earth, the reduced speed of sound on Mars ($a_{Mars} = 0.72a_{Earth}$) [5] results in more rapidly approaching $M = 1$ for a given velocity. To determine the maximum reference velocity we use the information that insects typically operate well below the compressibility regime at $M < 0.1$ such that $M_{max} = 0.1$. The maximum wing velocity is defined as the velocity at the wing tip and is constrained by the Mach number and speed of sound as

$$U_{tip} = 2\pi f\Phi R = M_{max}a_{Mars}.$$  (8)

Because the reference velocity is taken at the $R_2$ location, we can express $U_{ref}$ in terms of $U_{tip}$ as

$$U_{ref} = R_2 U_{tip}.$$  (9)

**Step 2. Iterate over $Re$ such that the corresponding wing size and motion generates lift that balances the weight:**

This step requires the iteration starting from a guessed value for the required $Re$ to allow for a properly scaled wing with the generated lift balancing the weight. Assuming an initial value of Reynolds number $Re_0$ allows solving for the estimated wing size by

$$c^n = \frac{\mu Re^n}{\rho U_{ref}},$$  (10)

where $n$ is the iterator index. The estimated wingspan and area can be determined as

$$R^n = c^n AR,$$

$$S^n = c^n R^n.$$  (11)

The mean lift $\langle C_{LNN} \rangle$ can be evaluated with the known values of $k$, $AR$, and $Re^n$ from the neural-network trained model such that
\[ \langle L \rangle^n = \frac{1}{2} \rho U_{ref}^2 S n (C_L)_{NN}^n. \]  

(12)

The index is advanced as \( n = n+1 \) until \( \frac{\langle L \rangle^n - W}{W} < 0.01 \% \). When this condition is satisfied, the converged values are set such that \( Re = Re^c, c = c^c, \) and \( R = R^c, \) resulting in a wing that is properly scaled to generate the required lift, \( 2\langle L \rangle = 2\langle L \rangle^c = W. \) We use a root finder to determine the converged value of \( Re^c. \)

**Step 3.** Solve for remaining kinematics:

The flapping amplitude \( \Phi \) is determined from the reduced frequency in hover \( k \) as

\[ \Phi = \frac{1}{2k \cdot AR}. \]  

(13)

The flapping frequency \( f \) can be expressed in terms of the reference velocity (Eq. (9)), wingspan, (Eq. (11)), and flapping amplitude (Eq. (13)) as

\[ f = \frac{U_{ref}}{2\pi\Phi R_2}. \]  

(14)

Note that only three of the five dimensionless parameters (\( AR, k, \) and \( Re \)) are varied in the above approach for determining \( c, R, f, \) and \( \Phi. \) This is because the pitch amplitude \( A \) is fixed at 45\(^\circ\), due to lift being maximized at this angle, and the wing tip Mach number \( M_{tip} \) is fixed at 0.1 to avoid compressibility effects. However, the effect of \( A \) is present in the data-driven CFD model for \( \langle C_L \rangle_{NN} \) as a low value of the pitch angle would result in a proportionally low \( \langle C_L \rangle \) [28,29].

**3 Results and discussion**

**3.1 Family of solutions for Mars flapping wing robots of various masses**

The scaling method can be used to determine a family of solutions for dynamically similar flapping wing motion on Mars for vehicles of various masses. The approach described in Section 2.4 is applied for a range of masses \( m \), allowing the relationships between the aspect ratio, Reynolds number, and kinematics to be investigated. We consider three discrete aspect ratios: \( AR = 2, 4, \) and \( 6 \) to cover the range of insect-inspired values. The reduced frequency values are in the insect flight regime, i.e. \( k = 0.2 \) and \( 0.6, \) such that the flapping amplitude is constrained within an upper bound of \( \Phi = 72^\circ \) (when \( k = 0.2 \) and \( AR = 2 \)) and lower bound of \( \Phi = 8^\circ \) (when \( k = 0.6 \) and \( AR = 6 \)).

Figure 5a shows a trend of increasing wingspan as the vehicles mass and aspect ratio increase. This agrees with the general scaling for a variety of flight vehicles where wing length has been shown to increase as a function of vehicle mass [49]. Similar trends of increasing \( Re \) with increased \( m \) can be found in Fig. 5b. The wing size must increase to
generate sufficient lift and $Re$ is proportional to the wing size through the chord length $c$ (Table 1). One of the main features is that the values of $Re$ are within the insect inspired regime of $Re < 10,000$, except for the case of $m \approx 1$ kg, $AR = 2$, and $k = 0.2$. This represents an upper bound of dimensionless parameters for this scaling model. The ability to maintain a relatively low value of $Re$ is again because $Re$ directly scales with the fluid density $\rho$ which is extremely low in the Martian atmosphere.

The general trend exhibited by the flapping frequency in Fig. 5c is that $f$ reduces with respect to increased vehicle mass $m$. This trend is similar to animal flight: larger birds flap more slowly than smaller insects. On the lower end of the weight spectrum $\mathcal{O}(10^{-6})$ kg, mosquitoes and fruit flies flap at frequencies of around 800 [50] and 200 Hz [51], respectively. On the upper end of the weight spectrum, wandering albatrosses $\mathcal{O}(10^0)$ kg and cape pigeons $\mathcal{O}(10^{-1})$ kg flap at, 2.5 and 5.6 Hz, respectively [52]. Lastly, the flapping amplitude in Fig. 5d is seen to be constant with changes in $m$ since it is purely a function of the inputs $k$ and $AR$ in our scaling method, although this is not necessarily an observation in natural fliers. Thus, for a wing with given $AR$ and desired $k$, the flap amplitude is solved via Eqn. (13).

### 3.2 Solutions for $m = 1, 10, 100,$ and $1000$ g flapping wing robots on Mars in hovering flight

In Section 3.1., we determined a continuous range of vehicle masses and the emerging trends from the bioinspired scaling model. Here, we extend the results by using the scaling model to generate results for several different vehicles of desired total mass and verify those results with NS solutions. Specifically, we test the question of whether the resulting vehicles are sufficiently scaled such that the resulting lift from the NS simulations balances the vehicle weights on Mars. The vehicle mass, aspect ratio, and reduced frequency of the considered configurations are the design space for scaling vehicles with desired masses, which is summarized in Table 3. The Reynolds number and the mean lift coefficient are outputs of the scaling model.

The range of masses considered seeks to include vehicles that are on the order of insects up to that of Mars helicopter Ingenuity [4]. The goal here is to demonstrate that flapping wing vehicles can be properly scaled across a broad range of dimensional and dimensionless values, yet still generate sufficient lift to hover on Mars.

The results from the NS simulations can be found in Fig. 6, which shows the lift-to-weight ratio for the input vehicle mass $m$. For most cases, the lift-to-weight ratio $2 \langle L \rangle _{NS} W^{-1}$ is within 10% (the green band in Fig. 6) of the desired unity value, where $2 \langle L \rangle _{NS} W^{-1} = 1$ represents a case of the lift exactly balancing the weight of the vehicle on Mars. However, when $2 \langle L \rangle _{NS} W^{-1} > 1$, the vehicle is over-scaled, such that it produces more lift than required to maintain its weight on Mars. This is likely due to the fact that the data-driven CFD scaling method underpredicted the mean lift coefficient for the given set of input parameters. Similarly, when the ratio $2 \langle L \rangle _{NS} W^{-1} < 1$, the scaling method overpredicted the resulting mean lift coefficient, such that the vehicle is under scaled and produces slightly less lift than required to maintain hover.
The bioinspired model scaled the wings and kinematics to generate ±10% of the lift required for hover flight on Mars. This implies that, in general, flapping wing vehicles can be appropriately scaled to large sizes if the dimensionless parameters are accounted for properly, even if it requires wings that are over 1 m in length (Fig. 5). There is one exception. For the case of \( m = 1 \text{ kg}, \ AR = 2, \ \text{and} \ k = 0.2 \), (red marker in Fig. 6) the generated lift is around 85% of the lift required. This relatively low lift value is likely due to the scaling method using a reduced order neural network model to capture the effects of a highly nonlinear aerodynamic mechanism.

We can further investigate the solution space by comparing the physical parameters of an example Mars flight vehicle from the scaling model to flying animals of comparable characteristics such as \( m, \ AR, \ \text{and} \ k \). This comparison illustrates how the resulting flapping wing robots on Mars differ from their biological counterparts in order to maintain dynamic similarity and achieve sufficient lift on Mars to balance their weight. This comparison can be found in Table 4 where “small” (1 gram) and “medium” (10 gram) flapping wing vehicles scaled for Mars are compared to a bumblebee and hummingbird on Earth. It can be seen that the solutions for Martian flight resemble biological fliers in both the dimensional and dimensionless parameters, except for one parameter, the wing area \( S \). As discussed in our previous work [6,13] and captured in the present scaling method, the most efficient way to augment the reduced density of the Martian atmosphere is through the use of large wings. This is not only more effective than scaling the kinematics, but it also allows the dimensionless parameters to remain in the bioinspired regime, while achieving kinematics that are physically implementable (i.e. \( \Phi < 90^\circ \) and \( f \) is on the order of terrestrial FWMAVs [14]), assuming sufficient actuator torque is available.

### 3.3 Exploitation of bioinspired lift-enhancement mechanisms for hovering on Mars

The proposed bioinspired scaling method hinges on the ability of dynamically similar motion to generate forces that benefit from the unsteady lift-enhancing mechanisms of insects on Earth. It is essential to understand the aerodynamic behaviors that generate sufficient lift to hover in the ultra-low-density Mars atmosphere. To test if the resulting Mars flight vehicles utilize the insect unsteady mechanisms, we analyze the lift production resulting from the Navier-Stokes equation solutions of the 1, 10, 100, and 1000 g configurations. Furthermore, we investigate the resulting flow structures for a representative configuration, i.e. the 10 g solution.

We can investigate the aerodynamic behavior of the vehicles by investigating the lift coefficient time history and the corresponding vortex dynamics shown in Fig. 7. The vortex dynamics provide a qualitative understanding of the flow behavior through the Q-criterion. High values of Q are indicative of coherence in the vortex structures, which are locations of low pressure in the flowfield.

The cycle-averaged lift coefficient \( \langle C_L \rangle \) (Fig. 7a) is sufficiently high to balance the weight of the vehicles in hover for these configurations. This was also illustrated by the lift-to-weight ratio (Fig. 6) being nearly unity. The time histories of the lift coefficient \( C_L \) in Fig. 7a reveal a trend that is similar to those produced by insects on Earth. Each half-stroke is characterized by a dominant lift peak during the middle of each half-stroke when the
instantaneous wing velocity is highest, leading to a high value of $C_L$ due to the attached leading edge vortex (LEV) seen in Fig. 7b. This attached LEV is characteristic of the delayed stall mechanism [24,40], where the presence of high vorticity near the wing’s leading-edge results in a substantial negative pressure gradient from the bottom to top surface of the wing. This pressure imbalance is a main contributor to the generation of lift for the flapping wing motion.

Near the end of a half-stroke the LEV becomes unstable and sheds from the wing (Fig. 7c), resulting in a reduction of $C_L$. The rotational lift mechanism during this interval also enhances lift [25]. During the rapid rotation of the wings at the beginning and end of each stroke, lift is enhanced due to additional circulation being generated which is manifested in the form of attached trailing edge vortices (Fig. 7d).

These same unsteady lift enhancement mechanisms to generate sufficient lift for hover were observed for all considered Mars flight vehicle solutions. This demonstrates the power of the proposed scaling method. Despite the three orders of magnitude difference in the vehicle masses $m$ (1 gram to 1000 grams) and a thirty-fold difference in the wingspan $R$ (8 cm to 240 cm), all of the flapping wing vehicles considered for flight on Mars utilize unsteady lift enhancement mechanisms in a similar fashion to insects on Earth. This indicates that the physical size of the vehicle does not necessarily restrict the ability to leverage insect-like aerodynamic mechanisms to generate sufficient lift for hover. As long as the relevant dimensionless parameters are accounted for and fall within the insect-inspired regime, flapping wing vehicles with large wings can successfully hover on Mars.

### 3.4 Power Required for Bioinspired Flight on Mars

In addition to understanding the aerodynamic mechanisms at play in achieving insect-inspired hovering on Mars, it is important to consider the corresponding power required such that payload mass and flight time metrics can be calculated. There are two sources of power required for flapping wing motion: the inertial power and the aerodynamic power. The inertial power is the power that is required to accelerate and decelerate any object in a vacuum. The aerodynamic power is the component required to overcome the aerodynamic forces opposing the wing motion during each flapping cycle. For each component, we consider the contributions due to the flapping and pitching motion of the wing. We can define [33] the power required as

$$ p_\psi(t) = \phi[I_\psi \ddot{\psi} \dot{M}_\psi^{aero}] $$

$$ p_\alpha(t) = \alpha[I_\phi \dot{x} \dot{M}_\phi^{aero}] $$

where $p_\psi$ and $p_\alpha$ are the flapping and pitching components of power, respectively. Here, the overdots represent the time rate of change of the corresponding angle. $M_\psi$ and $M_\alpha$ are the flapping and pitching aerodynamic moments about the $x$ (flapping) and $y$ (pitching) axes (Fig. 1) calculated from the CFD simulations. Similarly, $I_\psi$ and $I_\phi$ are the respective flapping and pitching mass moments of inertia. The power is thus comprised of inertial (first term) and aerodynamic (second term) components in Eqn. (15). For a quarter-elliptic wing
with uniform thickness and density, the flapping moment of inertia is \( I_\phi = m_w R^2 / 4 \) and the pitching moment of inertia is \( I_\alpha = m_w c^2 \rho \).

For the present analysis, we consider the mass of two wings to be 2.7% of the total vehicle mass based on the average data reported across a wide range of insects [56,57]. Although there may be some scaling effects on the wing-to-body mass ratio associated with vehicle masses ranging from 1 gram to 1 kilogram, this assumption is consistent with the bioinspired design in that this is an additional (structural) dimensionless parameter that we expect to maintain between the flapping wing vehicles on Mars and insects on Earth. Additionally, it is within the wing-to-total mass fraction found in Earth-based flapping wing MAVs – e.g. 2.4% for the KUBeetle-S [18], 1% for the Nano Hummingbird [16], and 0.83% for the Harvard Robofly [23].

During the course of a flapping period, the mechanical power required will take on both positive and negative values due to differences in signs between the angular velocities and moments (Eqn. (15)). We neglect negative power under the assumption that deceleration of the wing is aided by aerodynamic damping and requires much less metabolic energy than an equivalent amount of positive work [33,58]. Under this assumption, the negative values of power are neglected after each component of power is individually solved (Eqn. (15)). We only consider the positive power based on this definition [33] given as

\[
P_i(t) = \Xi[p_i(t)],
\]

where \( i \) is the index for either the pitch component \( \phi \) or flap component \( \alpha \), and \( \Xi(x) \) is defined by

\[
\Xi(x) = \begin{cases} 
  x & \text{if } x > 0 \\
  0 & \text{if } x \leq 0 
\end{cases}.
\]

The total power is the summation of the components of positive power given as

\[
P(t) = P_\phi(t) + P_\alpha(t).
\]

The total specific power is the power normalized by the vehicle mass

\[
P^*(t) = \frac{P(t)}{m}.
\]

Figure 8 contains the time history of moments and power for the case considered in Fig. 7, namely the vehicle with \( m = 10 \) g, \( AR = 4 \), and \( k = 0.2 \). In general, the inertial power is the dominant source of power due to the large wings required to generate sufficient lift in thin atmosphere on Mars [6]. The inertial and aerodynamic flap moments are generally nonzero due to the flapping motion being nearly sinusoidal and continuously changing (Fig. 8a). However, the inertial pitching component is nearly zero around each quarter stroke due to a constant pitch angle being maintained during these intervals. Additionally, the aerodynamic
pitch moment is small, but generally nonzero, due to maintaining the desired pitch profile against the lift and drag forces acting about the pitch axis. The trends in the power reflect those of the moments in Fig. 8a – the pitch power peaks around the stroke reversals when there are large rotational accelerations. The aerodynamic components of forces and power are nearly an order of magnitude less than the inertial components. This is similar to the low blade Lock numbers for helicopter operation on Mars [47]. Thus, the total power is primarily due to the positive components of inertial flap and inertial pitch power.

Figure 9 contains the time-averaged (Eq. (2)) values of power for the 36 solutions in the design space (Table 3) across various vehicle masses, aspect ratios, and reduced frequencies. Under the assumption that the wing mass is 2.7% the vehicle mass, the aerodynamic component of power is more sensitive to changes in mass compared to the inertial power. Furthermore, the dominance of the inertial component of power decreases as the vehicle mass approaches $O(10^3)$ kg.

Figure 9 also demonstrates that the power increases with increasing aspect ratio and reduced frequency. A larger aspect ratio causes a larger aerodynamic moment arm and moment of inertia, resulting in the increased power. Moreover, a larger reduced frequency for a fixed aspect ratio requires a reduction in the flapping amplitude, thus requiring a combination of a larger planform area and flapping frequency, leading to increased power as well. This is observed in Fig. 9 by the reduced frequency having a significant impact on increasing the inertial power while having almost no effect on the aerodynamic power. Such scaling can be demonstrated by considering the inertial power for a quarter-elliptic flapping wing undergoing purely harmonic motion (i.e. $\phi(t) = \Phi \sin 2\pi ft$). In this case the inertial component of flap power can be expressed as

$$p_{\phi}^{\text{inertial}}(t) = \dot{\phi} I_q \ddot{\phi} = m \pi^3 f^3 R^2 \Phi^2 \sin 4\pi ft.$$ (20)

The inertial power scales with flapping frequency to the third order but scales with flapping amplitude and wing size to the second order.

To compare the power required for Martian flight using the current scaling method compared to insect flight on Earth, the mean specific power $\langle P^* \rangle$ is plotted in Fig. 10. It is clear that the scaling method presented here generates solutions that require one to three orders of magnitude more specific power to operate when the vehicle is near the mass of an insect $O(10^{-3})$ kg. This is consistent with our previous work [6] for a bumblebee-like vehicle on Mars of $m = 0.213$ g, $k = 0.315$, and $AR = 3.3$. As the vehicle size increases for lower aspect ratio wings, the total specific power required can reduce to an order similar to that of insects ($O(10^2)$ W kg$^{-1}$). This is due to the fact that the vehicles of 1 gram require much higher flapping frequencies compared to those of larger vehicle masses, as discussed in Fig. 5c. The combination of both large flapping frequencies and large wings for 1-gram vehicles lead to a specific power requirement that can be up to three orders of magnitude higher than insects on Earth [58] due to the adverse scaling of power associated with these parameters (Eqn. (20)).
There is a bioinspired strategy to reduce the required inertial power. Insects, birds, and bats all exhibit some form of wing flexibility [59,60]. One well-established reason for this is the reduction in power for chordwise flexible wings compared to rigid wings [32,61]. Chordwise flexible wings passively deform due to the balance of aerodynamic, inertial, and elastic restoring forces acting on them. In this case, the inertial pitch power can reduce to zero [6]. Additionally, for a wing that has a torsional spring located at its root and is actuated at its resonance frequency, the flapping component of inertial power theoretically reduces to zero [6]. Similar compliant mechanisms have been physically implemented to reduce the inertial power to only 2% of the entire mechanical required for flapping wing motion [62]. Under these design considerations, the power for a vehicle using such idealized flexible wings with torsional springs at the wing roots is only comprised of the aerodynamic power [19]. This assumes that an idealized flexible wing could achieve the same flap and pitch profiles as considered for the rigid wings in this study. Although we do not simulate fully flexible wings through coupling a 3D anisotropic structural model to our NS solver, we are interested in understanding the low power that could be achieved in the limit of a fully compliant wing requiring no inertial actuation power.

In Fig. 11, we examine the application of this bioinspired strategy for the baseline vehicle masses which require the least amount of power from the present scaling method ($AR = 2, k = 0.2$). For these baseline cases, the specific power trends for rigid and fully flexible wings (i.e. wings with chordwise flexibility and a torsional spring placed at the root) are plotted in Fig. 11a. Flexible wings can result in an order of magnitude reduction in specific power, such that the specific power to fly on Mars is on the same order as that of an insect on Earth despite the Martian vehicle mass being nearly three orders of magnitude larger than the representative insect masses on Earth.

The flight times $t_f$ and payload masses $m_p$ for the baseline flexible wing cases are shown in Fig. 11b. We consider the flight time to be calculated as [63],

$$ t_f = \frac{S_b m_b}{\langle P \rangle / e}, $$

where $S_b$ is the specific energy density of the battery, $m_b$ is the battery mass, $\langle P \rangle$ is the mean power required, and $e$ is the electrical-to-mechanical efficiency of the actuator and associated power electronics. We consider the case where total mass $m$ is comprised of the battery mass $m_b$ and payload mass $m_p$ and the associated battery-payload mass-fraction is $\mu = m_b/m_p$. When $\mu = 0$, $m = m_p$, and there is no battery included, resulting in $t_f = 0$. Conversely, when $\mu = 1$, $m = m_b$, and the entire vehicle is comprised of the battery such that $t_f$ is maximum and $m_p = 0$. The ‘payload’ is defined such that it includes all of the masses that are not the battery – the structures, sensors, control actuators, electronics, etc.

The results in Fig. 11b are calculated under the assumptions that $e = 1$ (no loss of efficiency) and $S_b = 500$ kJ kg$^{-1}$, a typical value for lithium polymer batteries [64]. The battery-payload mass-fraction $\mu$ is varied from 0 to 1 for each vehicle mass considered in order to demonstrate the spectrum of achievable payload masses and flight times. Only the results for $k = 0.2$ are shown in Fig. 11b as there is little variation in aerodynamic power,
and therefore flight time and payload as \( k \) varies (Fig. 9). Under these assumptions, the payload as a function of flight time is relatively constant up to around \( \mu = 0.5 \), after which the payload significantly decreases for increased flight time. Payloads approaching 1 kg and flight times on the order of 100 minutes can be achieved for the vehicles considered under the assumptions of idealized flexible wings (requiring no inertial power), no loss of transmission efficiency, and a typical lithium polymer battery specific energy density (500 kJ kg\(^{-1}\)). The payload of 1 kg and flight time on the order of 100 minutes are in the limiting cases of the vehicle mass being comprised of only payload and only battery, respectively. This is an order of magnitude larger than compared to Earth-based FWMAVs of mass in the range \( O(10^0 - 10^1) \) grams [17]. However, this increase in larger \( t_f \) on Mars can be attributed in part to the reduced gravity and lift force required for a given vehicle mass on Mars as compared to Earth. These theoretical limits for flight times and payloads can be used for assessing flapping wing flight vehicle performance that benefits idealized flexible wings.

4 Concluding remarks

This study builds on our prior work of achieving hovering flight on Mars using bioinspired flapping wing motion based on a bumblebee with enlarged wings [6]. Using the present scaling method which leverages a 3D Navier-Stokes trained neural network model, approximate wing size properties and kinematics are determined such that sufficient lift is generated to achieve hover on Mars. This method was confirmed by 3D Navier-Stokes solutions for vehicles that varied from 1 gram to 1 kg and had a broad range of dimensionless parameters. Despite using wings that are larger than typical insect wings, the dimensionless parameters governing the high lift coefficient of insects are maintained in the present work.

The trends revealed in the scaling method are useful in understanding the limits of achieving insect-inspired flapping wing solutions for aerial vehicles on Mars as well as determining the vehicle parameters to supply to the NS solver. Based on a given flapping wing vehicle configuration, we can computationally determine the aerodynamic characteristics before designing a physical solution. This will allow for a more informed and efficient design process of a flapping wing flyer capable of flight on Mars.

Results indicate that, when idealized flexible wings are used, payload masses up to 1 kg and flight times on the order of 100 minutes are achievable using this scaling method. These values are achieved in the theoretical limiting cases of the vehicle masses being comprised solely of payload or battery, respectively. A payload of this magnitude can allow for a large suite of sensors useful for Mars exploration missions. A vehicle that can stay aloft on the order of 100 minutes can offer informed route planning information to the ground-based rovers. Additionally, the ability to generate vehicles of relatively small mass and wingspan but substantial flight time and payload would allow a robust fleet of flight vehicles to explore Mars in concert with each other and the existant Mars exploration vehicles. Although wing flexibility and mass distribution considered in this work are idealized, the auspicious results warrant future investigations of a higher order flexible wing model and increased fidelity of the system design as a whole.
Additional future work can include coupling the scaling method with our existing flight dynamics solver to determine the controls required for trimmed, hovering flight of a 6 degree-of-freedom flapping wing air vehicle on Mars. Investigation into maximizing flight time and minimizing power with an optimizer can be conducted as well. Lastly, the scaling method proposed here can be used to develop a high-level analysis of the flapping wing vehicle considered as an entire system, instead of focusing on the aerodynamics and resulting power alone, similar to our ongoing work [65].

Acknowledgments

This work was in part supported by the NASA Innovative Advanced Concepts program under the grant 80NSSC18K0870 and partly by the University of Alabama in Huntsville through supplemental research funding. Jeremy Pohly is supported by the NASA/Alabama Space Grant Consortium, NASA Training Grant NNX15AJ18H.

Appendix

Appendix A: Grid and Time Sensitivity Studies

Time and spatial sensitivity analyses were performed for each of the three aspect ratios considered in this study. For each aspect ratio (AR = 2, 4, and 6), 4 grids per aspect ratio were generated (using Pointwise mesh generation software) to find a solution that was independent of the grid size. The size and cell count for each grid can be found in Table A1. The details of the converged grid used for AR = 4 can be found in Fig. A1. Each simulation in the grid sensitivity analysis was run with 500 time steps per period and simulated for 1 flapping period. Additionally, a time sensitivity analysis was run at four different numbers of steps per period (125, 250, 500, and 1000) for the converged grid based on the spatial sensitivity analysis. The kinematics for this study were simplified to simple harmonic motion with the flapping angle governed by a sine wave and the pitching motion 90 degrees out of phase, represented by a cosine wave. The pitch axis was located at the leading edge. These studies were conducted for Re = 10000, k = 0.3, U_{ref} = 1, \rho = 1, c=1, A = 45°. The third ‘baseline’ grid (23×46×92) with 631800 cells and 500 time steps per period yields sufficiently converged solutions for lift for each aspect ratio as shown in Fig. A2.

Table A1.

| Grid (chord×span×normal) | Cells | Total Cells |
|--------------------------|-------|-------------|
| Coarse 10×20×40          | 46930 |
| Medium 15×30×60          | 168200|
| Baseline 23×46×92        | 631800|
| Fine 34×68×136           | 2091874|
Figure A1.
Illustrations of the converged baseline grid (23×46×92, 631800 cells) for \( AR = 4 \) in a) an isometric view of the full domain, b) a planar slice of the computational mesh in the wing plane, and c) a detailed view of the mesh around the wing. Similar trends are present in the converged grids for the other two aspect ratios considered.
Figure A2. 
Time histories, mean values, and percent differences of $\langle C_L \rangle$ for a, c, e) grid sensitivity and b, d, f) time step sensitivity studies. Percent difference is for $\langle C_L \rangle$ with respect to fine grid (34x68x136). The blue lines represent the spatially and temporally converged baseline cases.

Appendix B: Validation of 3D NS framework for a single, rigid flapping wing at low $Re$

To validate the simulation of solving the 3D NS equations for a single flapping wing, we compare results from our present framework to that of Lee et al. [29] in Fig. B1. This simulation considers a quarter-elliptic wing of $AR = 3.2$, $Re = 6283$ (with $Re$ defined in
the present work), $Ro = 2.93$, $A = 45^\circ$. Note that $Ro$ is the Rossby number, which is an additional dimensionless parameter that arises when the wing pivot location is not placed at the intersection of the flapping and pitching axis (i.e. there is an offset between the pivot location and the wing root). There are no Rossby number considerations in the present work, thus it is not considered in the design space.

![Figure B1](image.png)

**Figure B1.**
Time history of the lift, drag, and power coefficients as compared to Lee et al. [29] for a 3D NS simulation of a quarter-elliptic wing.

**References**

[1]. Coppola M, McGuire KN, De Wagter C, and de Croon GCHE, “A Survey on Swarming With Micro Air Vehicles: Fundamental Challenges and Constraints,” Frontiers in Robotics and AI, vol. 7, 2020.

[2]. Petrosyan A, Galperin B, Larsen SE, Lewis SR, Määttänen A, Read PL, Renno N, Rogberg LPHT, Savijärvi H, Siili T, Spiga A, Toigo A, and Vázquez L, “The Martian Atmospheric Boundary Layer,” Reviews of Geophysics, vol. 49, Sep. 2011, p. RG3005.

[3]. Sullivan R, Greeley R, Kraft M, Wilson G, Golombek M, Herkenhoff K, Murphy J, and Smith P, “Results of the imager for mars pathfinder windsock experiment,” Journal of Geophysical Research: Planets, vol. 105, Oct. 2000, pp. 24547–24562.

[4]. Balaram J (Bob), Canham T, Duncan C, Golombek M, Grip HF, Johnson W, Maki J, Quon A, Stern R, and Zhu D, “Mars Helicopter Technology Demonstrator,” AIAA-2018-0023, 56th AIAA Aerospace Sciences Metting, Kissimmee, Florida, January 8–12: 2018.

[5]. Shrestha R, Benedict M, Hrishikeshavan V, and Chopra I, “Hover Performance of a Small-Scale Helicopter Rotor for Flying on Mars,” Journal of Aircraft, vol. 53, 2016, pp. 1160–1167.

[6]. Bluman J, Pohly JA, Sridhar M, Kang C-K, Landrum DB, Fahimi F, and Aono H, “Achieving bioinspired flapping wing hovering flight solutions on Mars via wing scaling,” Bioinspiration & Biomimetics, vol. 110, May 2018, pp. 428–433.

[7]. Sane SP, “The aerodynamics of insect flight,” The Journal of Experimental Biology, vol. 206, 2003, pp. 4191–4208. [PubMed: 14581590]

[8]. Shyy W, Aono H, Kang C-K, and Liu H, An Introduction to Flapping Wing Aerodynamics, New York, NY: Cambridge University Press, 2013.

[9]. Xiao T, and Liu H, “Exploring a bumblebee-inspired power-optimal flapping-wing design for hovering on Mars based on a surrogate model,” Journal of Biomechanical Science and Engineering, vol. 15, 2020, pp. 20-00001–20-00001.

[10]. Bolster D, Hershberger RE, and Donnelly RJ, “Dynamic similarity, the dimensionless science,” Physics Today, vol. 64, 2011, pp. 42–47.

*Acta Astronaut.* Author manuscript; available in PMC 2022 March 01.
[11]. White FM, Fluid Mechanics, 7th Edition, 2011.
[12]. Barenblatt GI, Scaling, Cambridge University Press, 2003.
[13]. Pohly JA, Kang C-K, Sridhar M, Landrum DB, Fahimi F, Bluman JE, Aono H, and Liu H, “Payload and Power for Dynamically Similar Flapping Wing Hovering Flight on Mars,” 2018 AIAA Atmospheric Flight Mechanics Conference, Reston, Virginia: American Institute of Aeronautics and Astronautics, 2018, pp. 1–11.
[14]. Nakata T, Liu H, Tanaka Y, Nishihashi N, Wang X, and Sato A, “Aerodynamics of a bio-inspired flexible flapping-wing micro air vehicle,” Bioinspiration and Biomimetics, vol. 6, 2011.
[15]. De Croon GCHE, Groen MA, De Wagter C, Remes B, Ruijsink R, and Van Oudheusden BW, “Design, aerodynamics and autonomy of the DelFly,” Bioinspiration and Biomimetics, vol. 7, 2012.
[16]. Keennon M, Klingebiel K, and Won H, “Development of the Nano Hummingbird: A Tailless Flapping Wing Micro Air Vehicle,” AIAA-2012-588, 50th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition, Nashville, Tennessee, January 9–12; 2012, pp. 1–24.
[17]. Phan HV, Aurecianus S, Au TKL, Kang T, and Park HC, “Towards Long-Endurance Flight of an Insect-Inspired, Tailless, Two-Winged, Flapping-Wing Flying Robot,” arXiv preprint arXiv:2005.06715, 2020.
[18]. Phan HV, Aurecianus S, and Park HC, “KUBeetle-S: An insect-like, tailless, hover-capable robot that can fly with a low-torque control mechanism,” International Journal of Micro Air Vehicles, vol. 11, 2019.
[19]. Design RI, Tu Z, Fei F, Zhang J, and Deng X, “An At-Scale Tailless Flapping-Wing Hummingbird and Experimental Validation,” 2020, pp. 1–15.
[20]. Tang J, Vieru D, and Shyy W, “Effects of Reynolds number and flapping kinematics on hovering aerodynamics,” AIAA Journal, vol. 46, 2008, pp. 967–976.
[21]. Shyy W, Aono H, Chimakurthi SK, Trizila P, Kang C-K, Cesnik CES, and Liu H, “Recent progress in flapping wing aerodynamics and aeroelasticity,” Progress in Aerospace Sciences, vol. 46, 2010, pp. 284–327.
[22]. Bluman JE, and Kang C-K, “Wing-wake interaction destabilizes hover equilibrium of a flapping insect-scale wing,” Bioinspiration & Biomimetics, vol. 12, Jun. 2017, p. 046004. [PubMed: 28463224]
[23]. Wood RJ, “The First Takeoff of a Biologically Inspired At-Scale Robotic Insect,” IEEE Transactions on Robotics, vol. 24, Apr. 2008, pp. 341–347.
[24]. Ellington CP, van den Berg C, Willmott AP, and Thomas ALR, “Leading-edge vortices in insect flight,” Nature, vol. 384, Dec. 1996, pp. 626–630.
[25]. Dickinson MH, Lehmann F-O, and Sane SP, “Wing rotation and the aerodynamic basis of insect flight,” Science, vol. 284, Jun. 1999, pp. 1954–1960. [PubMed: 10373107]
[26]. Birch JM, and Dickinson MH, “The influence of wing-wake interactions on the production of aerodynamic forces in flapping flight,” Journal of Experimental Biology, vol. 206, 2003, pp. 2257–2272.
[27]. Sane SP, and Dickinson MH, “The aerodynamic effects of wing rotation and a revised quasi-steady model of flapping flight,” The Journal of experimental biology, vol. 205, 2002, pp. 1087–1096. [PubMed: 11919268]
[28]. Nakata T, Liu H, and Bomphrey RJ, “A CFD-informed quasi-steady model of flapping-wing aerodynamics,” Journal of Fluid Mechanics, vol. 783, 2015, pp. 323–343. [PubMed: 27346891]
[29]. Lee YJ, Lua KB, Lim TT, and Yeo KS, “A quasi-steady aerodynamic model for flapping flight with improved adaptability,” Bioinspiration & Biomimetics, vol. 11, Apr. 2016, p. 036005. [PubMed: 27121547]
[30]. Pohly J, Salmon J, Bluman J, Nedanchezian K, and Kang C-K, “Quasi-Steady versus Navier–Stokes Solutions of Flapping Wing Aerodynamics,” Fluids, vol. 3, Oct. 2018, p. 81.
[31]. Shyy W, Aono H, Chimakurthi SK, Trizila P, Kang C, Cesnik CES, and Liu H, “Recent Progress in Flapping Wing Aerodynamics and Aeroelasticity,” Progress in Aerospace Sciences, vol. 46, 2010, pp. 284–327.
[32]. Kang C, Aono H, Cesnik CES, and Shyy W, “Effects of flexibility on the aerodynamic performance of flapping wings,” Journal of Fluid Mechanics, vol. 689, 2011, pp. 32–74.
[33]. Berman GJ, and Wang ZJ, “Energy-minimizing kinematics in hovering insect flight,” Journal of Fluid Mechanics, vol. 582, 2007, p. 153.
[34]. Sun M, and Xiong Y, “Dynamic flight stability of a hovering bumblebee,” Journal of Experimental Biology, vol. 208, Feb. 2005, pp. 447–459.
[35]. Nabawy MRA, and Crowther WJ, “Aero-optimum hovering kinematics,” Bioinspiration & Biomimetics, vol. 10, 2015, p. 044002. [PubMed: 26248884]
[36]. Eldredge JD, and Jones AR, “Leading-Edge Vortices: Mechanics and Modeling,” 2019, pp. 75–104.
[37]. Zheng L, Hedrick TL, and Mittal R, “Time-Varying Wing-Twist Improves Aerodynamic Efficiency of Forward Flight in Butterflies,” PLoS ONE, vol. 8, 2013, pp. 1–10.
[38]. Du G, and Sun M, “Effects of unsteady deformation of flapping wing on its aerodynamic forces,” Applied Mathematics and Mechanics, vol. 29, Jun. 2008, pp. 731–743.
[39]. Nabawy MRA, and Crowther WJ, “Optimum hovering wing planform,” Journal of Theoretical Biology, vol. 406, 2016, pp. 187–191. [PubMed: 27329340]
[40]. Shyy W, and Liu H, “Flapping Wings and Aerodynamic Lift: The Role of Leading-Edge Vortices,” AIAA Journal, vol. 45, Dec. 2007, pp. 2817–2819.
[41]. Bhat SS, Zhao J, Sheridan J, Hourigan K, and Thompson MC, “The leading-edge vortex on a rotating wing changes markedly beyond a certain central body size,” Royal Society Open Science, vol. 5, 2018.
[42]. Liu H, and Aono H, “Size effects on insect hovering aerodynamics: An integrated computational study,” Bioinspiration and Biomimetics, vol. 4, 2009.
[43]. Chen D, Kolomenskiy D, Nakata T, and Liu H, “Forewings match the formation of leading-edge vortices and dominate aerodynamic force production in revolving insect wings,” Bioinspiration & Biomimetics, vol. 13, 2017, p. 016009. [PubMed: 29052556]
[44]. Wang Q, Goosen JPL, and Van Keulen F, “Optimal pitching axis location of flapping wings for efficient hovering flight,” Bioinspiration and Biomimetics, vol. 12, 2017.
[45]. Aono H, Liang F, and Liu H, “Near- and far-field aerodynamics in insect hovering flight: an integrated computational study,” Journal of Experimental Biology, vol. 211, 2008, pp. 239–257.
[46]. Trizila P, Kang C-K, Aono H, Shyy W, and Vishal M, “Low-Reynolds-Number Aerodynamics of a Flapping Rigid Flat Plate,” AIAA Journal, vol. 49, Apr. 2011, pp. 806–823.
[47]. Grip HF, Johnson W, Malpica C, Scharf DP, Mandić M, Young L, Allan B, Mettler B, Martin MS, and Lam J, “Modeling and identification of hover flight dynamics for NASA’s Mars helicopter,” Journal of Guidance, Control, and Dynamics, vol. 43, 2020, pp. 179–194.
[48]. Bluman JE, Kang C-K, Landrum DB, Fahimi F, and Mesmer B, “Marsbee - Can a Bee Fly on Mars?,” AIAA-2017-0328, 55th AIAA Aerospace Sciences Meeting, Grapevine, Texas, January 9–13: 2017.
[49]. Liu T, “Comparative scaling of flapping- and fixed-wing flyers,” AIAA Journal, vol. 44, 2006, pp. 24–33.
[50]. Bomphrey RJ, Nakata T, Phillips N, and Walker SM, “Smart wing rotation and trailing-edge vortices enable high frequency mosquito flight,” Nature, vol. 544, 2017, pp. 92–95. [PubMed: 28355184]
[51]. Fry SNSN, Sayaman R, and Dickinson MH, “The aerodynamics of hovering flight in Drosophila,” J. Exp. Biol, vol. 208, 2005, pp. 2303–2318. [PubMed: 15939772]
[52]. Pennycuick CJ, “Wingbeat frequency of birds in steady cruising flight: New data and improved predictions,” Journal of Experimental Biology, vol. 199, 1996, pp. 1613–1618.
[53]. Dudley R, and Ellington CP, “Mechanics of Forward Flight in Bumblebees: I. Kinematics and Morphology,” Journal of Experimental Biology, vol. 148, Oct. 1990, pp. 19–52.
[54]. Chai P, and Millard D, “Flight and size constraints: hovering performance of large hummingbirds under maximal loading,” The Journal of experimental biology, vol. 200, Nov. 1997, pp. 2757–63. [PubMed: 9418032]
[55]. Tobalske BW, Warrick DR, Clark CJ, Powers DR, Hedrick TL, Hyder GA, and Biewener AA, “Three-dimensional kinematics of hummingbird flight,” Journal of Experimental Biology, vol. 210, 2007, pp. 2368–2382.

[56]. Ellington CP, “The Aerodynamics of Hovering Insect Flight. II. Morphological Parameters,” Philosophical Transactions of the Royal Society of London Series B-Biological Sciences, vol. 305, 1984, pp. 17–40.

[57]. Willmott AP, and Ellington CP, “The mechanics of flight in the hawkmoth Manduca sexta. II. Aerodynamic consequences of kinematic and morphological variation,” The Journal of experimental biology, vol. 200, 1997, pp. 2723–45. [PubMed: 9418030]

[58]. Sun M, and Du G, “Lift and power requirements of hovering insect flight,” Acta Mechanica Sinica, vol. 19, 2003, pp. 458–469.

[59]. Lehmann F-O, Gorb S, Nasir N, Schutzner P, and Schützner P, “Elastic deformation and energy loss of flapping fly wings,” Journal of Experimental Biology, vol. 214, Sep. 2011, pp. 2949–2961.

[60]. Curet OM, Swartz SM, and Breuer KS, “An aeroelastic instability provides a possible basis for the transition from gliding to flapping flight,” Journal of The Royal Society Interface, vol. 10, Mar. 2013, p. 20120940.

[61]. Eldredge JD, Toomey J, and Medina A, “On the roles of chord-wise flexibility in a flapping wing with hovering kinematics,” Journal of Fluid Mechanics, vol. 659, Sep. 2010, pp. 94–115.

[62]. Lau GK, Chin YW, Goh JTW, and Wood RJ, “Dipteran-insect-inspired thoracic mechanism with nonlinear stiffness to save inertial power of flapping-wing flight,” IEEE Transactions on Robotics, vol. 30, 2014, pp. 1187–1197.

[63]. Whitney JP, and Wood RJ, “Conceptual design of flapping-wing micro air vehicles,” Bioinspiration and Biomimetics, vol. 7, 2012.

[64]. Karpelson M, Whitney JP, Wei GY, and Wood RJ, “Energetics of flapping-wing robotic insects: Towards autonomous hovering flight,” IEEE/RSJ 2010 International Conference on Intelligent Robots and Systems, IROS 2010 - Conference Proceedings, 2010.

[65]. Dunne SH, Palma GE, Pohly JA, Mesmer B, Landrum DB, and Kang C-K, “System Analyzer for a Bioinspired Mars Flight Vehicle System for Varying Mission Contexts,” AIAA Scitech 2020 Forum, Reston, Virginia: American Institute of Aeronautics and Astronautics, 2020, pp. 1–13.
Fig. 1. Schematic illustration of the key parameters for a) the wing with pitch axis location at the leading edge ($y_W$) (as used by some FWMAVs [14,23]) and b) the flapping motion and the pitching motion. The wing parameters are determined by considering a semi-elliptic wing, similar to the wing planforms used in practical applications of FWMAVs [14].
Fig. 2.
Flapping and pitching motion used in study. All cases consider $\kappa = 0.01$ to generate nearly sinusoidal flapping, $\delta = 2.0$ to generate a modified square wave, and $A = 45.0^\circ$. $\Phi$ is dependent on the input values of $AR$ and $k$. 
Fig. 3.

a.) Two-layer, densely connected sequential neural network model. b.) Comparison between the predicted values of $\langle C_L \rangle_{NN}$ from the neural-network model and the true values $\langle C_L \rangle_{NS}$ from the CFD simulations.
Fig. 4.
Overview of steps involved in scaling method. Step 2 uses a root finder to iteratively solve for the lift required to balance the vehicle weight based on the data-driven CFD model $\langle c_L \rangle_{NN}$. 

Inputs: $m$, $AR$, $k$ 

Step 1: Set $U_{ref}$ 

Step 2: Iteratively scale $c$, $R$, and $Re$ so that 

$$2\langle L \rangle_{NN} = W$$ 

Step 3: Solve kinematics $f$ and $\Phi$ 

Outputs: $c$, $R$, $f$, $\Phi$
Fig. 5.
The resulting a) wingspan, b) Reynolds number, c) flapping frequency, and d) flapping amplitude for a family of dynamically similar flapping wing robots on Mars for various masses. The results are obtained using the scaling method (Section 2.4) for a range of $m$, $AR = 2$, 4, and 6 with $k = 0.2$ and 0.6.
Fig. 6.
NS confirmation of the scaling method for generating vehicles of masses varying between 1 gram and 1 kg and a range of dimensionless input parameters. $2\langle L\rangle_{NS}$ is the total lift from the two wings. The green band represents ±10% of the vehicle weight $W$. 
Fig. 7.

a) 3D NS lift coefficient mean values (top) and time histories (bottom) for the cases of \( m = 1, 10, 100, \) and 1000 grams, with \( AR = 4 \) and \( k = 0.2 \) during the second flapping period. The gray bar graph values are those predicted by the neural network model \( \langle C_L \rangle_{NN} \).

Contour plots of the iso-surfaces of Q-criterion \( (Q = 5) \) colored by the spanwise component of vorticity for the case of \( m = 10 \) grams are shown for b) \( t/T = 1.25 \) with attached LEVs leading to high \( C_L \), c) \( t/T = 1.38 \) when the LEVs have detached leading to a reduction in \( C_L \), and d) \( t/T = 1.44 \) during the generation of additional circulatory lift during rapid wing pitching. Note that 3D NS solutions are for one wing only. The second wing and the body are included for visualization purposes only. The body is not to scale.
Fig. 8.
a) Moments and b) power for a 10 gram flapping wing vehicle. Both the components of power $p_i$ as well as the total positive power $P$ are presented.
Fig. 9.
Inertial and aerodynamic components of cycle-averaged positive power for a) $AR = 2$, b) $AR = 4$, and c) $AR = 6$. d) The corresponding total power for each vehicle mass considered.
Fig. 10.  
Mean specific power for the rigid Mars cases considered in the current study compared to insects on Earth [58] and the solution presented in our previous work for flight on Mars. Note that reduced frequency values of 0.2, 0.4, and 0.6 are marked by circles, squares, and upright triangles, respectively. Additionally, the values in this figure do not consider any wing flexibility.
Fig. 11. 

a) Specific power for the rigid and the idealized flexible baseline case of $AR = 2$ and $k = 0.2$ on Mars compared to insects on Earth [58]. b) Flight time versus payload mass for various vehicles on Mars using idealized flexible wings with $k = 0.2$, $AR = 2, 4, 6$, and varying $\mu$. 

Acta Astronaut. Author manuscript; available in PMC 2022 March 01.
Table 1.

Dimensionless parameters, their definitions, and typical values which govern the high lift coefficients of insects.

| Dimensionless Quantity | Symbol | Definition | Insect range [8] |
|------------------------|--------|------------|------------------|
| Aspect ratio           | $AR$   | $\frac{R^2}{S}$ | $2 \leq AR \leq 6$ |
| Reduced frequency (hover) | $k$   | $\frac{\pi fc}{U_{ref}}$ | $0.1 \leq k \leq 0.4$ |
| Reynolds number        | $Re$   | $\frac{U_{ref} c}{v}$ | $O(10^2 - 10^4)$ |
| Pitch amplitude        | $A$    | $A$ | $20^\circ \leq A \leq 60^\circ$ |
| Wing tip Mach number   | $M_{tip}$ | $\frac{U_{tip}}{a}$ | $M_{tip} \leq 0.1$ |
| Lift coefficient       | $C_L$  | $\frac{L}{1/2 \rho U_{ref}^2 S}$ | $O(10^{-3} - 10^0)$ |
Table 2:

Parametric design space values for 125 CFD simulations to explore effects of dimensionless parameters on $\langle C_L \rangle$. 100 randomly selected simulations were used as the training data for the neural-network model. The remaining 25 simulations were then used as the testing data (Fig. 3b) for the model.

| Dimensionless Quantity       | Symbol | Parametric Study Values |
|------------------------------|--------|-------------------------|
| Aspect ratio                 | AR     | 2, 3, 4, 5, 6           |
| Reduced frequency (hover)    | $k$    | 0.2, 0.3, 0.4, 0.5, 0.6 |
| Reynolds number              | $Re$   | 100, 500, 1000, 2000, 10000 |
| Pitch amplitude              | $\alpha$ | 45°                     |
| Wing tip Mach number         | $M_{tip}$ | $M_{tip}=0.1$          |
Table 3:
Design space of 36 configurations used to test and verify the bioinspired scaling model.

| Input parameter         | Symbol | Values       | Units   |
|-------------------------|--------|--------------|---------|
| Vehicle mass            | $m$    | 1, 10, 100, 1000 | grams   |
| Aspect ratio            | $AR$   | 2, 4, 6      | ---     |
| Reduced frequency (hover)| $k$    | 0.2, 0.4, 0.6 | ---     |
Table 4:
Comparison of select designs from scaling method with biological counterparts.

|                  | bumblebee on Earth [53] | 1 gram vehicle on Mars (present work) | hummingbird on Earth [54,55] | 10 gram vehicle on Mars (present work) |
|------------------|-------------------------|--------------------------------------|-----------------------------|----------------------------------------|
| $AR$             | 3.3                     | 2.0                                  | 4.1                         | 2.0                                    |
| $k$              | 0.15                    | 0.20                                 | 0.10                        | 0.20                                   |
| $Re$             | 1950                    | 413                                  | 11000                       | 1250                                   |
| dimensionless parameters | $\alpha$ | $\Phi$ | $M_{in}$ | $\langle C_L \rangle$ | $m$ | $W$ | $f$ | $R$ | $S$ |
| $\alpha$         | $\sim$ 45              | 45                                   | 45                          | $\sim$ 20                              |
| $\Phi$           | 58                      | 72                                   | 75                          | 72                                      |
| $M_{in}$         | 0.038                   | 0.1                                  | 0.049                       | 0.1                                    |
| $\langle C_L \rangle$ | 1.05                   | 0.69                                 | 1.46                        | 0.75                                   |
| $m$              | 0.18                    | 1.0                                  | 8.4                         | 10.0                                   |
| $W$              | 0.00172                 | 0.0037                               | 0.0824                      | 0.037                                  |
| $f$              | 155                     | 51                                   | 23                          | 17                                      |
| $R$              | 1.3                     | 6.2                                  | 8.0                         | 8.5                                     |
| $S$              | 0.53                    | 19.0                                 | 16.0                        | 8.81                                    |

*Note: The dimensionless parameter calculations in this table use the definitions in the current study (see Table 1). However, the original morphological values provided by each researcher listed in this table are used as corresponding inputs. This is because dimensionless parameter definitions can vary among different researchers.*