Abstract. In achieving missions for Mars exploration, the concept of exploration technique based on air vehicles has been not established adequately yet and is one of active research topics. Two challenges of very low atmospheric density and rough Mars terrain in the development of such air vehicles indicate that unconventional low Reynolds number aerodynamics and flight control systems are a must to be explored and established. In this study, we classify the platforms for Mars exploration with a specific focus on the possible designs of air vehicles. We then demonstrate the prototype design of a bioinspired flapping micro air vehicle (fMAV), which is weighted 2.4 - 3.0 g, equipped with a X-type wing and a wingspan of 12 -15 cm. An integrated study of flexible wing aerodynamics and passive dynamic flight stability of the MAV is performed through a combination of flexible wing kinematics and force measurements and computational approaches. Our results show that the clap-and-fling mechanism is indeed realized by the prototype four-winged MAV and the flexible wing deformation even further enhance its effects. Moreover, an extended study on the passive dynamic flight stability of the MAV's forward flight based on a linear theory indicates that the MAV is very likely of dynamical stability even with no active feedback control system. We further discuss about the possible bioinspired designs of robust and high-capability flapping-wing platforms for Mars Exploration.

1 Introduction

Mars has answers to many important planetary science questions. Of essential significance is the excellent preservation of the geologic record of early Mars, the period more than 3.5 billion years ago when life began on Earth. Therefore, Mars offers the opportunity to address questions about how and whether life arose elsewhere in the solar system, about processes of planetary evolution on a planet that has undergone notable changes through time, and about the potential coupling between biological and geological history [39, 1].

Successful Mars exploration by either rovers or other possible platforms with robust design is essential to achieve above goals. There are several types of platform proposed and developed for Mars exploration. Rovers, orbiters, and combination of them have been well known as well as contributed to Mars exploration in the past decade [9, 29]. While the concept of exploration tech-
nique based on air vehicles has been not established adequately yet and is one of active research topics.

Micro air vehicles (MAVs) are now an active and well-integrated research area, attracting participation from a wide range of talents. With a maximal dimension of 15 cm and nominal flight speeds of around 10 m/s, MAVs are desired to be capable of performing missions such as environmental monitoring, surveillance, and rescue in natural disasters. MAVs normally operate in a Reynolds number regime of $10^4 - 10^5$ or lower, in which most natural flyers including insects, bats, and birds, and the prominent feature of MAVs’ aerodynamics, in general, is characterized by large-scale vortex flow structure and hence highly unsteady [43]. Furthermore, due to their light-weight and low flight speed and the interactions between moving wings and those vortices, the MAVs’ flight characteristics are substantially affected by environmental factors such as wind gust, which may lower the flight stability and hence makes the flight control a very challenging problem. Like natural flyers, the wing structures of MAVs are often flexible and tend to deform during flight. Consequently, the aero/fluid and structural dynamics of these flyers are closely linked to each other, making the entire flight vehicle difficult to analyze [41].

In the past decade, there has been a remarkable increasing in research and development of the MAVs and numerous vehicle concepts, including fixed-wing, rotary-wing, and flapping-wing, have been proposed [31, 35, 36, 46, 40]. As a vehicle becomes a size smaller than 15 cm normally corresponding with a Reynolds number less than $10^5$, the fixed wing designs encounter fundamental challenges in low lift-to-drag ratio and unfavorable flight control. There are merits and challenges associated with rotary and flapping wing designs with a smaller size and at lower Reynolds numbers. All the successful flapping-wing MAVs developed till now have flexible and light wings as observed in biological flyers in nature [54], which indicates that wing flexibility is likely to have a significant influence on the resulting aerodynamics as well as the flight stability [41, 40, 55, 30]. Therefore, flapping flexible wing aerodynamics is of great importance not only in uncovering the novel mechanisms in insect and bird flights but also in designing efficient flapping flight vehicles.

In this paper, we first give a review on the platforms designed for Mars exploration, which have been proposed and developed in the past decade involving rovers, obiters, and aero vehicles. In particular, we highlight several concepts and platforms for atmospheric exploration on Mars including fixed-wing, flapping-wing, rotating-wing, and so forth. Then, after giving an overview of the state-of-art of flapping MAVs we describe in detail a recently developed, bio-inspired flapping-wing MAV with a specific focus on a systematic analysis of the flexible wing aerodynamics and passive forward-flight stability. Specific attention is paid on a so-called ‘clap and fling’ mechanism which is achieved by a crank system, not only because such mechanism is observed in insect flight and thought to enhance the aerodynamic force generation [51], but also because such physical interaction can affect the in-flight deformation of flexible flapping wing and hence aerodynamic performance. Furthermore, we discuss about the insect flight-based possible implication for developing robust and high-capability flapping-wing platforms for Mars exploration.

2 Platforms Designed for Mars Exploration

2.1 Mars Exploration

Recently, a workshop called “Concepts and Approaches for Mars Exploration” has been held in U.S.A. [39, 1] and discussion at the workshop focused on the development of high-pay-off missions potentially beginning with the 2018 launch opportunity, which are responsive to the scientific goals articulated by the National Research Council Planetary Science Decadal Survey [3], to the Mars Exploration Program Analysis Group Goals, and to the US President’s challenge of sending humans to the vicinity of Mars in the decade of the 2030s. According to the latest version of the document regarding Science Goals, Objectives, Investigations, and Priorities in Mars exploration [4] four main goals are follows:

1. Determine if life ever arose on Mars – Does life exist, or did it exist, elsewhere in the universe? This is perhaps one of the most compelling questions in science, and Mars is the most promising and accessible place to begin the search;

2. Understand the processes and history of the climate on Mars – Climate and atmospheric studies are key to understanding how the planet may have been suited for life and how major parts of the surface have been shaped, and are directly relevant to our understanding of the past, present, and future climate on Earth. Additionally, characterizing the environment of Mars is also necessary for
the safe implementation of future robotic and human spacecraft missions to the planet;

3. Determine the evolution of the surface and interior of Mars;


Therefore, successful Mars exploration by either rovers or other possible platforms with robust design is essential to achieve above goals.

2.2 Type of Platform Designed for Mars Exploration

There are several types of platform proposed and developed for Mars exploration. Rovers, orbiters, and combination of them have been well known as well as contributed to Mars exploration in the past decade [9, 29]. While the concept of exploration technique based on air vehicles has been not established adequately yet and is one of active research topics. Following are brief summaries of platforms designed for Mars exploration.

Rover:

Ground rovers [9, 29, 50], for example, Curiosity, have significantly contributed to objectives and goals presented in previous section (also see Figure 1). Recently, the European Space Agency (ESA) has presented a plan to search for signs of past and present life on Mars using a rover on 2018 (see Figure 1). Some of limitations of ground rovers are limited searchable areas and speed. To overcome those limitations, a new concept of rover [5] (see Figure 2) and rover-based Mars exploration concepts are proposed and studied.

Orbiter:

Orbiters, for instance, Mars Reconnaissance Orbiter, have contributed to understand the processes and history of the climate on Mars. NASA and ESA has a
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plan to study Martian atmospheric trace gases and their sources and conduct surface environment measurement on 2014 (Mars Atmosphere and Volatile EvolutioN: MAVEN) and 2016 (Exobiology on Mars: ExoMars), respectively (see Figure 1). Generally, the orbiter is capable of sweeping the planet, but suffers from low spatial resolution and drastic diminution of the strength of radar return signal strength with range that falls with the fourth power of the distance.

Aerovehicles:

As mentioned previously, one of main goals in Mars exploration is to search for microclimates and study lower atmosphere climate processes (i.e. atmospheric exploration on Mars). This goal can easily be addressed by in situ atmospheric measurements performed by an aerovehicle. Moreover, Mars explorations by collaborative platform of rovers and aerovehicles would have far greater capability than either in isolation.

An aircraft flying at an altitude of 2 kilometres has an eight order of magnitude advantage in return signal strength compared to that obtained by an orbiter operating 200 kilometres. The aircraft also would have a two order of magnitude advantage in spatial resolution.

Following challenges are in development of air vehicles for Mars exploration, especially in aerodynamic design point of view:

1. Very low atmospheric density: This causes all-conventional aircraft designs encounter the same limitation. The aircraft must be fast to generate sufficient lift. Also the aircraft will fly under low Reynolds numbers condition.

2. Rough Mars terrain: This would make it virtually impossible for conventional aircraft to successfully land and take off again.

Several concepts and platforms for atmospheric exploration on Mars have been developed and studied including fixed-wing, flapping-wing, rotating-wing, and so forth (see Figure 3). Here we highlight some interesting one as follows:

1) Fixed-wing 1-1) Aerial Regional-scale Environmental Surveyor (ARES) [20, 45, 19, 57, 38, 22, 24]. ARES is an instrumented, rocket-powered, well-tested robotic airplane platform (see Figure 3A-1). It flies between one to two kilometres to collect and transmit previously unobtainable high spatial measurements relevant to the NASA Mars Exploration Program and the exploration of Mars by humans. ARES has been selected to proceed into Phase A as part of the Mars Scout Mission competition in 2002 and receiving a second Category 1 science rating during the Mars Scout competition in 2006. After that the ARES mission concept has continued to mature technologically and scientifically, adjusting to reflect the current exploration goals for assessment of human exploration at Mars and enabling technologies for future missions.

1-2) Cannon Assisted Flying Exploration (CAFE) [13]. CAFE is a concept for Mars atmosphere and surface exploration that was proposed to deploy compressed air cannon on the surface of Mars that launches aerial exploration vehicles (Figure 3A-2).

1-3) Mars Gas Hopper [37, 61, 60, 59]. Mars gas hopper is a novel concept for propulsion of a robust Mars flight and surface exploration vehicle that utilizes indigenous CO$_2$ propellant to enable greatly enhanced mobility (Figure 3A-3).

2) Flapping-wing Flapping wing propulsion is other possible propulsive system. High lift-generating capability under low Reynolds number flight conditions provides an innovative solution to the dilemma of atmospheric flight on Mars [7, 10, 11, 8]. The concept of entomopter [7, 10, 8] and Solid State Aircraft [11, 8] (see Figure 3B) has been proposed as an alternative to the need to fly very fast at Mars. This flyer will follow vortex-based lift enhancements that insects employ on Earth [42]. Such vortex generation and shedding produces higher wing lift coefficients, on the order of 5 compared to maximum lift coefficients of 1 to 1.2 for conventional airfoils. This high lift-generating capability allows insects to fly, hover and maneuver as they do. Wing-flapping drones would need to account for Mars’s low air pressure (much more difficult than on Earth) and operate in a very low Reynolds number regime. In addition, there are practical size limitations for vehicles that could be deployed on mis-
Bioinspired Air Vehicles Designed for Mars Exploration

3 Bioinspired Flapping-Wing Ornithopter

3.1 An Overview on Flapping MAVs

Flapping wing propulsion, as seen in bio-flyers of insects and birds, posses high lift-generating capability under low Reynolds number flight conditions and therefore may provide an innovative solution to the dilemma of atmospheric flight on Mars. Sightorson et al. [44] showed that the flapping wing vehicle is less sensitive to velocity perturbations in all aerodynamic forces and moments than the rotocraft, except for the forward/backward direction force.

Two key factors in designing MAVs are the wing size and the gross weight. Allowable mass restricts the composition of the actuators, power source, or materials, constraining the wing kinematic, frequency, size, or available aerodynamics forces. Therefore, one of the biggest challenges in building flapping MAVs, in particular for insect-sized or smaller one, is realizing wing kinematics within the severely restricted mass [52]. Here we give an overview on the existing flapping MAVs by their wing sizes and total masses (see Figure 4), as well as the technologies employed.

The upper limit of the wing size is determined not only by aerodynamics but also by available material for the wing. Since flapping motion causes not only aerodynamic force but also inertial force due to the wing mass, the wing base and frame structures should possess enough strength to tolerate the oscillating load and bending moments. In other words, high stiffness-weight ratio is desired for the material of flapping wings in order to reduce the inertia force and resultant bending moment.

In the past decade, most flapping MAVs have been developed with a wingspan ranging from $100$ to $10^{-2}$ m and a mass of $100$ kg to $10^{-2}$ kg, [11, 34, 12]. Electric motors and conventional gear-crank mechanisms are often used to create wing motions. For relatively bigger MAVs [21, 47] the payload can afford some avionics such as vision systems or autonomous control systems; and by processing the captured images with a ground station, autonomous obstacle avoidance can be realized. In these electric ornithopters, the active wing motion is often 1-DOF (degree of freedom) flapping unlike birds or insects demonstrating not only flapping motion but also feathering and lead-lag motions. Their flight maneuver is realized with a rudder or elevators of the tail wing like conventional fixed-wing aircrafts, or a tail rotor like helicopters. A few exceptional ornithopters, however, are able to actively feather the main flapping wings and achieve maneuvering flight without ladders or elevators [2], in which multi servo actuators are employed for additional DOF of wing or body motions.

Recently a tiny fly-like MAV [27] with a wingspan of $30$ mm, a weight of $80$-milligram and a flapping frequency of $120$ Hz is developed, which is equipped with high-power-density piezoelectric flight muscles and built by means of a manufacturing methodology capable of rapidly prototyping articulated, flexure-based sub-millimeter mechanisms. With a modular approach to flight control that relies on limited information about the robot’s dynamics, the MAV can achieve a tethered but unconstrained stable hovering and basic controlled flight maneuvers.
Figure 3. Concepts for Mars Exploration with Aerial Vehicles. (A-1) ARES [19, 38, 57, 45], (A-2) CAFE [22], (A-3) Mars gashopper airplane concept [24, 61, 60, 59], (B-1) Entomopter [7, 10, 8], (B-2) Wing-flapping drone [11, 8], (C-1) Mars hovercraft [56, 18, 58], (C-2) Mars VTOL UAC rotor [23], (D) Aerocoasting [48], (E) Mars balloon [53]
Bioinspired Air Vehicles Designed for Mars Exploration

Clarification of flapping wing aerial robots in terms of mass and wingspan.

All of the successful flapping-wing MAVs developed up [21, 47] to this point have flexible and light wings such as those observed in natural biological flyers [54], which indicates that wing flexibility is likely to have a significant influence on the resulting aerodynamics, as well as the flight stability [55, 30, 33, 40]. In a sense, flapping flexible-wing aerodynamics is of great importance not only in uncovering the novel mechanisms of insect and bird flight, but also in designing efficient flapping flight vehicles. In the following, we present a systematic study of the aerodynamics and flight stability associated with a recently developed bio-inspired flapping wing MAV [34]. This prototype MAV, has four flexible wings and employs the clap and fling mechanism, which is achieved by a prototype crank system. The clap and fling mechanism is utilized here not only because it is commonly observed in insect flight and thought to be capable of enhancing the aerodynamic force generation [51], but also because such physical interaction can affect the in-flight deformation of flexible flapping wings and hence aerodynamic performance.

3.2 Clap-and-Fling Mechanism in Insect Flight

Clap-and-fling is a lift enhancement mechanism, which was first discovered in insect flight by Weis-Fogh [51]. This relates to the wing-wing interaction phenomenon, which takes place at dorsal stroke reversal (see Figure 5). During the clap phase, the leading edges of the paired wings approach each other and the wing rotation (pronation) about the leading edges occurs until the v-shaped gap between the wings disappears. In the fling phase, the wings rotate about their trailing edges forming a gap in between. Investigations on insects and birds showed that as well as being used continuously during the flight, some species utilize this mechanism for a limited time in order to generate extra lift, especially while carrying loads or during the take-off phase.

3.3 A Bioinspired Flapping-wing MAV

Inspired by the clap-and-fling we developed a prototype flapping-wing micro air vehicle, which as illustrated in Figure 6 is equipped with an X-type wing.
The X-type wing is made of two pairs of wings and achieves three times clap-and-fling at the side and at the top in a wing beat. The wingspan is designed to be around 12 cm with a wing length of 60 mm and a wing chord length of 30 mm at wing base, of a size as observed in hawkmoth and hummingbird. The wing has a semi-elliptic planform, which is made of the polyethylene film with a thickness of 0.3 mm and the carbon rod with a diameter of 0.3 mm at leading edge. The mean chord length is calculated to be 23.6 mm. The gearbox is fabricated by cutting the acrylonitrile-butadiene-styrene (ABS) resin so as to ensure a nice match among the motor (MK04S-10, DIDENTL), gears and wing hinges. With a speed-reduction ratio of 60/12 teeth of the idler gear, the crank is mounted to link and actuate the two pairs of wings on the 60 teeth final gear. The gearbox system, the crank and the wings are connected by a carbon rod of a diameter of 0.5 mm with the tail, the rudder, the receiver and the remote-controller. The rudder is controlled by a magnetic actuator (Hinge Act, PLANTRACO) so as to move laterally, which is weighted 0.23 g and can provide sufficient control power. The remote-controller with infrared ray offers two channels to control both the motor frequency and the rudder angle. The rechargeable lithium polymer battery (FR30SC, FULLRIVER) is utilized as the power source. With all the parts mounted together our flapping MAV weighs less than 3 g in toto and is able to fly with time duration up to 6 minutes, a maximum height over 10 meters and a region of 20 meters by 20 meters. More details can be found in [34].

3.4 Flapping Wing Aerodynamics

To investigate the flexible wing aerodynamics, the high-speed camera (with a frame rate of 1000 per second) filming system is utilized to measure the flexible wing kinematics. Given that the flapping frequency of the MAV normally varies over a range of 20 Hz to 35 Hz, the recorded image sequences are able to provide sufficient temporal resolution for the flexible wing kinematics. The recorded image sequences are downloaded to a computer and the three-dimensional coordinates of these marked points are reconstructed by utilizing the commercial software, DippMotion (Ditect Corp.).

The kinematic model of the MAV’s wing is constructed by interpolating the reconstructed coordinates of the markers on the flapping wings. The displacements \(\mathbf{u}(t, x, y)\) at some point of the wing \((x, y)\) are interpolated by using a function of Fourier series, such as:

\[
\mathbf{u}(t, x, y) = \sum_{l=0}^{N_x} \sum_{m=0}^{N_y} \sum_{n=0}^{N_z} \left( \alpha(l, m, n)x^l y^m \cos(n\omega t) + \beta(l, m, n) x^l y^m \sin(n\omega t) \right)
\]

where terms \(\alpha\) and \(\beta\) are derived by the least square method. The wing surface grids are translated by \(u\) and the grid is regenerated on the basis of the hyperbolic grid generation scheme.

In order to evaluate the aerodynamic performance of the flexible wing MAV, we use a biology-inspired, dynamic flight simulator [32, 34, 6, 25, 26, 28, 32], which is designed to integrate the modelling of realistic wing-body morphology, realistic flapping-wing and body kinematics, and unsteady aerodynamics in biological flight. A realistic morphological model of the MAV’s wing (Figure 6) is constructed by tracing the outline of the wing planform. A uniform thickness is taken but with elliptic smoothing at the leading and trailing edge as well as at the tip. To deal with the complexity of the wing deformation and wing kinematics we use a multiblocked overset grid method, in which the wing grid is clustered to the wing surface with the minimum grid spacing adjacent to the wing surface controlled by the Reynolds number. The simulation is done as depicted in Figure 6 under the assumption that the left and right wings move and deform symmetrically.

The computational study is performed under the assumption of hovering flight condition. Given the mean chord length \(c_m\), as the reference length \(L_{ref}\), the mean wing tip velocity in hovering flight as the reference velocity \(U_{ref}\), which is proportional to \(U_{ref} = \omega R\), where \(R\) is the wing length and \(\omega\) is the mean angular velocity of the wing \((\omega = 2\Phi f\), where \(\Phi\) is the wing beat amplitude and \(f\) is the flapping frequency\), the Reynolds number in hovering flight can be reformed as

\[
Re = \frac{U_{ref} L_{ref}}{v} = \frac{2\Phi f R c_m}{v} = \frac{\Phi f R^2}{v} \left( \frac{4}{AR} \right)
\]

where the aspect ratio \(AR\) is in a form of \(AR = (2R)^2/S\), with a wing area of \(S = 2R c_m\). Note that the Reynolds number here is proportional to the wing beat amplitude, \(\Phi\), the flapping frequency, \(f\), a square of the wing length, \(R^2\), but proportional inversely to the aspect ratio of the wing, \(AR\). The reduced frequency that normally characterizing rotational versus translational speeds, is defined in case of hovering flights, such
as:

\[ k = \frac{\pi f L_{\text{ref}}}{U_{\text{ref}}} = \frac{\pi c_m}{2\Phi R} = \frac{\pi}{\Phi A R} \]  

(3)

Note that the reduced frequency \( k \) is proportional inversely to the beat amplitude \( \Phi \) and the aspect ratio \( AR \) of the wing. According to the measured data of the MAV’s mechanical model (\( c_m = 23.6 \text{ mm}, R = 60 \text{ mm}, \Phi = 1 \text{ rad}, f = 18.5 \text{ s}^{-1}, = 1.5 \times 10^{-5} \text{ m}^2/\text{s} \)), Re and \( k \) are calculated to be about 3400 and 0.59, respectively.

The flapping flexible wing aerodynamics is evaluated by both visualized near- and far-field flow structures around the flapping wings and integrated vertical and horizontal forces acting upon the MAV. As shown in Figure 8, the computed results show that a leading edge vortex (LEV) and hence a strong negative pressure region are generated on upper and lower wings during both of the half stroke. As observed in insect flapping flight [25], this LEV likely plays a key role in the lift and/or thrust force-production in the MAV flight. The vortex rings that are formed from the LEV, the tip vortex (TV) and the trailing edge vortex (TEV) are also observed, showing a similar pattern with those of insect flight [26]. Obviously, the strong negative pressure regions are detected between the upper right and left wings, which is induced by the clap and fling mechanism. In addition, the mean aerodynamic force is calculated to be 23.3 mN, which is in reasonable agreement with the measurement of a value of 26.46 mN. The mean force components of \( F_x \) and \( F_z \) generated by the upper wing are -4.2 mN and 0.2 mN, and, by the lower wing are -3.8 and 2.0 mN, respectively.

Wing deformations due to wing flexibility likely af-

FIGURE 7. (a) A mechanical flapping-wing MAV model. (b) A computational fluid dynamic model of MAV wings and a multi-block grid system. (c) Force measurement system. (d) Definition of displacements on wing surface.
Frequent streamlines, iso-vorticity surface and pressure contours on upper surface of flapping wings at each half stroke. Effects also the clap-and-fling mechanism. In the present study, we find that with the wing clap the rotational phase of both upper and lower wings at stroke reversal is nearly symmetric, while without the wing clap the rotation of the lower wing obviously exhibits a phase delay at stroke reversal. This implies that the clap and fling of a flexible wing can adjust the feathering angle near the wing tip at stroke reversal so as to avoid some unfavorable phase delay during wing rotation. As a result, the fling-induced additional circulation and the passive deformation-based flexible wing kinematics in total are very likely responsible for augmenting the aerodynamic force production effectively in the present four-winged MAV.

3.5 Passive Dynamic Flight Stability

A Linear Theory:

Aiming at analyzing the passive dynamic flight stability of insect flapping flight, we have recently developed a computational approach by introducing a linear and a nonlinear theory into the biology-inspired, dynamic flight simulator [14, 15, 16]. In this study, the linear theory is employed for the analysis of the passive dynamic stability in MAV’s forward flight. With the ‘rigid body’ assumption that the MAV body does not deform and hence has only 6 degrees of freedom (DoFs) the flapping wing effects on the flight system can be represented by the wingbeat-cycle-average aerodynamic and inertial forces and moments. Furthermore, the MAV’s motion is assumed to consist of small disturbances from the equilibrium condition. On the basis of the linearized equations of motion, the longitudinal dynamic flight stability can be considered with 3 DoFs: the forward, the dorso-ventral and the pitching disturbances.

The equations of motion may be then linearized by approximating the body’s motion as a series of small disturbance from a steady, symmetric reference flight condition, such that:

\[ \delta \dot{u} = H_u \delta u/m + H_w \delta w/m + H_q \delta q/m - g \delta \theta \]  
\[ \delta \dot{w} = V_u \delta u/m + V_w \delta w/m + V_q \delta q/m \]  
\[ \delta q = M_u \delta u/I_y + M_w \delta w/I_y + M_q \delta q/I_y \]  
\[ \delta \theta = \delta \dot{q} \]

where \( H_u, H_w, H_q, V_u, V_w, V_q, M_u, M_w, \) and \( M_q \) are the aerodynamic derivatives (\( H \) and \( V \) are the \( x \)- and \( z \)-components of the total aerodynamic forces, respectively, and \( M \) is the pitching moment); \( m \) is the mass of the insect; \( g \) is the gravitational acceleration; \( I_y \) is the pitching moment of inertia about \( y \) axis; \( \cdot \) represents differentiation with respect to time (\( t \)); the symbol \( \delta \) denotes a small disturbance quantity.

Then the non-dimensional forms of Eqs 4-7 in vector form can be expressed as:

\[ \delta \dot{x} = A \delta x(t) \]

where \( \delta x \) denotes the non-dimensional longitudinal state vector of \( \delta u^+, \delta v^+, \delta q^+, \delta \theta^+ \). The constant system matrix \( A \) is given by

\[
A = \begin{bmatrix}
X_u/m & X_w/m & X_q/m & g \\
Z_u/m & Z_w/m & Z_q/m & 0 \\
M_u/I_x & M_w/I_y & M_q/I_z & 0 \\
0 & 0 & 1 & 0
\end{bmatrix}
\]
the sign of the real part of the eigenvalue(*). If the real part is positive, the system is dynamically unstable; if the real part is negative, the system is dynamically stable [14, 15, 16].

Forward Flight Stability:
The disturbance from outside that the MAV undergoes is treated as the relative motion of the MAV from a reference flight condition (forward flight). And the three components of the disturbance, namely, the elevation in x- and z-axis and the pitching movement can be transformed to a horizontal velocity \( u \), a vertical velocity \( w \) and a pitching angular velocity \( q \) about the centre of mass, respectively. In order to estimate the aerodynamic derivatives, we consider three disturbance conditions for the three state variables \((u, w, q)\) separately.

Under the equilibrium condition (the reference flight condition), the MAV is observed to perform a forward flight at a speed of 1 m/s with a body angle of 61 degrees. As shown in Figure 9, the disturbances of horizontal, vertical and pitching angular velocities vary in a range of \([-0.05, 0.05]\). The vertical axis shows the difference between the disturbance and equilibrium. As observed in our previous studies of hawkmoth hovering flight [14, 15, 16], all the three curves show approximately linear variation. Accordingly the aerodynamic derivatives, \( H_u^+, H_w^+, H_q^+ \), \( V_u^+, V_w^+, V_q^+ \), \( M_u^+, M_w^+, M_q^+ \) can be calculated by taking the local tangents of the curves as given in Table 1.

Based on the computed aerodynamic derivatives, the system matrix is obtained, which results in four eigenvalues \( \lambda_1, \lambda_2, \lambda_3 \) and \( \lambda_4 \) with a pair of complex \( \lambda_{1,2} \) as shown in Table 2. These four eigenvalues represent three natural modes: a stable oscillatory motion and two subsidence modes. The state variables can be then obtained which correspond to the three eigenvectors (Table 3); these eigenvectors can be normalized so as to define a pitch–attitude disturbance \( \delta \theta^+ \) of 1 rad at a zero phase angle.

The eigenvalue of \( \lambda_{1,2} = -0.275 \pm 0.436i \) corresponds with the stable oscillatory mode, which results in the time being taken to half the disturbance values of approximately \( t_{\text{half}} = 2.52 \) periods, which indicates that the MAV takes approximately two wing beats to half the initial disturbance values. The fast subsidence mode is also stable with an eigenvalue of \( \lambda_3 = -0.1655 \), which results in \( t_{\text{half}} = 4.19 \). The slow subsidence mode, however, has a positive eigenvalue of \( \lambda_3 = 0.0968 \) but quite small, which leads to the time being taken to twice the disturbance values of approximately \( t_{\text{half}} = 7.16 \) periods, which indicates that the MAV can sustain its body attitude up to approximately seven wing beats when getting its the initial disturbance values doubled. In a word, while the initial value of the disturbance is unknown here and hence it is difficult to determine a precise timescale for the disturbance damping, the computed three eigenvalues and eigenvectors together very likely contribute to a dynamically stable one.

\[ \delta \theta^+ \]

Figure 9. Horizontal (H) and vertical (V) forces and pitching moments (M) under disturbances of horizontal, vertical, and pitching angular velocities.
3.6 Implication for Flapping-wing Vehicles for Mars Exploration

While ground exploration rovers would be main actors in the Mars sample return campaign during the coming decade, in order to conduct more efficient and robust rover-based atmospheric exploration on Mars, development of aerial platforms with flapping / rotating wing-based propulsions are needed. This would further contribute to the safe implementation of future robotic and human spacecraft missions to the plan.

With consideration of two major challenges of very low atmospheric density and rough Mars terrain in development of air vehicles for Mars exploration, we need to explore un-conventional aerodynamics and flight control systems, which should be specified for the flapping /rotating wing ornithopters workable on Mars. Luckily, we can learn and get hints from nature: the low Reynolds number aerodynamic designs of small birds, bats, and insects. Aerodynamics of such natural bioflyers, with the maximum dimension of O(10) centimeters or smaller, and weight of O(10) grams or lighter, intersect with some of the richest problems in aerospace engineering, in which highly unsteady three-dimensional boundary, large-scale vortical flows, unsteady and uncertain flight environment, aeroelasticity associated with anisotropic wing structure, and adaptive control are just a few examples of these problems. Such flyers are significantly more sensitive to wind gust and flight obstacles than larger flyers of passenger aircraft; their agility and spectacular flight performance, owing to their flexible, deformable wing structures as well as outstanding wing, tail, and body coordination, is achieved much better than any state-of-art man-made flight vehicles.

Therefore, a bioinspired flapping-wing platform for Mars exploration, if is used to accomplish a real mission, must have high flight capabilities as: 1) Flights under a wide range of forward velocities including hovering; 2) Flights with high acceleration and angular acceleration; and 3) Flights that are very robust to wind gusts. And such air vehicles need to have the abilities of 1) Large and quick control force/moment; 2) Small variations of aerodynamic force/moment when wind gusts are encountered; and 3) Sensors and actuators with short time-delay and high accuracy.

4 Conclusion

In this paper we have given a review on the platforms designed for Mars exploration involving rovers, obiters, and aero vehicles. Specifically, we have discussed about several concepts and platforms for atmospheric exploration on Mars including fixed-wing, flapping-wing, rotating-wing, and so forth and accordingly would suggest that conducting more efficient and robust atmospheric exploration on Mars does need development of aerial platforms with flapping/rotating wing-based propulsions. Two major challenges of very low atmospheric density and rough Mars terrain in development of air vehicles for Mars exploration indicate that un-conventional aerodynamics and flight control systems should be explored and specified for the flapping /rotating wing ornithopters. We may not be able to discover a perfect design from natural flyers of insects, birds and bats but we can definitely get inspiration from such smart bioflyers, which achieve remarkable performance in the similar low Reynolds number regime.

To provide with a prototype concept and platform of bioinspired flapping-wing MAVs, we have demonstrated a recently developed, flapping-wing MAV with a specific focus on a systematic analysis of the flexible wing aerodynamics and passive forward-flight stability. Our aerodynamic analyses have thereby given a comprehensive understanding of the aerodynamic effects based on the clap and fling mechanism on the four-winged flapping mechanism, indicating that the clap and fling mechanism observed in insect and bird flights is indeed utilized by the X-type wing MAV. Furthermore, the simulation-based analyses of the longitudinal passive dynamic stability of the four-winged MAV in for-
ward flight, though is conducted by means of a linear theory based on the eigenvalue analysis, shows that this flapping-wing MAV is likely capable to realize a dynamically stable forward flight under various disturbance conditions.

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References


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Table 3. Magnitudes and phase angles of each of three eigenvectors

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<thead>
<tr>
<th></th>
<th>Δ u</th>
<th>Phase angle</th>
<th>Δ w</th>
<th>Phase angle</th>
<th>Δ q</th>
<th>Phase angle</th>
<th>Δ θ</th>
<th>Phase angle</th>
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<tbody>
<tr>
<td>Stable oscillatory</td>
<td>0.701</td>
<td>29.5°</td>
<td>0.329</td>
<td>168°</td>
<td>0.516</td>
<td>122°</td>
<td>1.0</td>
<td>0°</td>
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<tr>
<td>Fast subsidence</td>
<td>0.346</td>
<td>0°</td>
<td>2.065</td>
<td>180°</td>
<td>0.165</td>
<td>180°</td>
<td>1.0</td>
<td>0°</td>
</tr>
<tr>
<td>Slow subsidence</td>
<td>0.099</td>
<td>180°</td>
<td>0.056</td>
<td>180°</td>
<td>0.097</td>
<td>0°</td>
<td>1.0</td>
<td>0°</td>
</tr>
</tbody>
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