Experimental force and wing motion measurements of a bioinspired flapping wing in a Martian density condition

Jesse Lee McCain

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EXPERIMENTAL FORCE AND WING MOTION MEASUREMENTS OF A BIOINSPIRED FLAPPING WING IN A MARTIAN DENSITY CONDITION

by

JESSE LEE MCCAIN

A THESIS

Submitted in partial fulfillment of the requirements for the degree of Master of Science in Engineering in The Department of Mechanical and Aerospace Engineering to The School of Graduate Studies of The University of Alabama in Huntsville

HUNTSVILLE, ALABAMA

2019
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(student signature)

(date)
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Submitted by Jesse Lee McCain in partial fulfillment of the requirements for the degree of Masters of Science in Aerospace Systems Engineering and accepted on behalf of the Faculty of the School of Graduate Studies by the thesis committee.

We, the undersigned members of the Graduate Faculty of The University of Alabama in Huntsville, certify that we have advised and/or supervised the candidate on the work described in this thesis. We further certify that we have reviewed the thesis manuscript and approve it in partial fulfillment of the requirements for the degree of Master of Science in Engineering.

Dr. Chung-Siwon Kang  
Committee Chair  
10/31/19  
(Date)

Dr. D. Brian Landrum  
10/31/19  
(Date)

Dr. Farzad Farshidi  
10/31/2019  
(Date)

Dr. D. Keith Hollingsworth  
Department Chair  
10/31/19  
(Date)

Dr. Shankar Mahalingam  
College Dean  
10/31/19  
(Date)

Dr. David Berkowitz  
Graduate Dean  
1/1/19  
(Date)
ABSTRACT

School of Graduate Studies
The University of Alabama in Huntsville

Degree Master of Science in Engineering College/Dept. Engineering/Mechanical and Aerospace Engineering

Name of Candidate Jesse Lee McCain

Title EXPERIMENTAL FORCE AND WING MOTION MEASUREMENTS OF A BIOINSPIRED FLAPPING WING IN A MARTIAN DENSITY CONDITION

A Mars flight vehicle could provide a third-dimension for ground-based rovers and supplement orbital observation stations, providing a much more detailed aerial view of the landscape as well as unprecedented survey of the atmosphere of Mars. However, flight on Mars is a difficult proposition. Due to very low atmospheric density, approximately 1.3% of sea level density on Earth, aircraft must fly approximately ten times faster, or be one hundred times lighter in weight than their Earth counterparts, to lift themselves on Mars. While traditional aircraft efficiency suffers in the low Reynolds number environment, flapping wing insect inspired flyers on Mars might be able to take advantage of the same lift enhancing effects as insects on Earth. In this thesis, the feasibility of using a bioinspired, flapping wing flight vehicle to produce lift in an ultra-low-density Martian atmosphere is investigated. A four-wing prototype, inspired by a
prior study, with a single wingspan of 12 cm with an area of 0.0070 m\(^2\) was placed in an atmospheric chamber to simulate Martian density. The peak-to-peak flapping amplitude was 35 deg for the upper wings and 30 deg for the lower wings, with flapping frequencies ranging from 5 to 18 Hz. Lift was measured by an ATI Nano-17 force transducer. Wing deformation was simultaneously tracked using a Vicon motion capture system. In Earth density conditions, the passive pitch wing deflection increased monotonically with flapping frequency. Conversely, in the Martian density environment, the passive pitch deflection angles did not follow a consistent pattern, sometimes even deflecting in the direction opposite of expected. When in the Martian density environment, the lift generated by the flapper was measured to be an order of magnitude greater than the inertial forces generated by the flapping motion. The lift generally increased with flapping frequency. However, when the flapping frequency was 14 Hz and between 17 and 19 Hz, the wing passive pitch angles were suboptimal. Nevertheless, the measured lift peaked at around 8 grams at 16 Hz. These measurements suggest that sufficient aerodynamic forces for hover on Mars can be generated for a 6-gram flapping wing vehicle.

Abstract Approval: Committee Chair
Department Chair
Graduate Dean
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<tr>
<td>$c$</td>
<td>Wing mean chord length</td>
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<td>$CFD$</td>
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<td>Flapping frequency</td>
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To my parents, and Abigail.
CHAPTER 1

INTRODUCTION

1.1 Background and Motivation

The exploration of our solar system has been a foremost goal of science since we began our first experiments with rocketry. First, we put a human in space, then landed man on the moon. Now, the focus of space exploration has shifted to the red planet, Mars. While landers and probes were sent to explore Mars as early as the 1960s\textsuperscript{1}, and rovers began to explore its surface in the 1990s\textsuperscript{2}, one of the main goals of Mars exploration is human colonization. A permanent settlement on the surface of Mars could allow for scientists to study a completely alien environment that formed around the same time as the Earth, and thus yield a better understanding of the formation of the solar system. Human habitation could also greatly speed up the process of surface exploration, as they could cover more ground than the Mars rovers in a shorter timeframe. Furthermore, explorers could negotiate terrain that would be impassable for a rover. However, before
they can be sent to Mars, a more in-depth study of the Martian atmosphere and surface must be completed.

One factor that handicaps rover exploration is the limited rover viewing range. As rover exploration covers a larger portion of the Martian surface, the chance that a rover will become mired or reach an impassable obstacle increases. Such an obstacle can require significant back tracking and, thus, large amounts of rover time to navigate around. The dangers of uneven terrain are magnified by the fact that the rovers cannot receive any assistance, deploy a winch, or use a ramp to attempt to free themselves, so the possibility of the rover freeing itself is unlikely.

Orbital imaging capability from missions like the Mars Reconnaissance Orbiter (MRO) can provide for more informed rover pathfinding. The MRO’s HiRISE camera is capable of taking large, high resolution pictures of the Martian surface with a pixel size of around 0.3 m meaning that the smallest features that it can make out are around 1.0 m in size. The orbiter also carries the Mars Color Imager (MARCI) that is used to track clouds and dust storms, enabling the orbiter to provide warning to rovers about incoming storms. Though satellite imaging is better than relying purely on the rover’s viewpoint, its limited resolution at Mars ground level means that its ultimate utility is fairly limited.

A lower flying vehicle could provide higher resolution imaging to better inform rover path planning. Aircraft could provide additional information about the terrain ahead, and, hence, allow for better use of rover mission time.
1.2 Challenges for Flight on Mars

However, it is challenging to fly on Mars. The force balance between a vehicle’s weight and lift (Eq 1) effectively summarizes the challenges to flying on Mars\(^5\). In cruise flight, the wing lift \(L\) offsets the weight \(W\) as

\[
W = mg_{mars} = L = \frac{1}{2} \rho_{mars} U^2 SC_L \tag{Eq 1}
\]

where \(C_L\) is the lift coefficient, and \(g_{mars}\), and \(\rho_{mars}\) are the Martian gravitational acceleration and atmospheric density, respectively\(^6\). The other variables are described as follows: \(U\) is the reference velocity, \(m\) is the vehicle mass, and \(S\) is the wing planform area\(^6\). Although \(g_{mars}\) is about one-third of the gravitational acceleration on Earth, the average Martian atmospheric density is only 1.3% of the air density on Earth\(^7,8\) (see Figure 1.1). Aerodynamic forces are proportional to the ambient fluid density, implying that conventional terrestrial flight vehicle designs generate insufficient lift on Mars. Furthermore, oxygen is absent in the Martian atmosphere, preventing the use of air-breathing propulsion\(^6\).

The low density also leads to a relatively low operational Reynolds number \(Re\) of \(O(10^2)–O(10^3)\)\(^7,9\). The dynamic viscosity coefficient on Mars is \(1.5 \times 10^{-5}\) kg/(m-s)\(^10\), similar to that on Earth - \(1.8 \times 10^{-5}\) kg/(m-s). In these low Reynolds number regimes, the lift coefficients of traditional fixed wing and rotary wing aircraft are significantly reduced\(^9,11\). To augment the reduced lift coefficient, \(C_L\), all conventional aircraft designs must fly faster (higher \(U\)) with a much lower wing loading \(m/S\) to compensate\(^6\).
Several intriguing aerial vehicles have been proposed to overcome the challenges associated with flying on Mars. A comprehensive review of these vehicles can be found in the literature\(^\text{13}\) (Section 2.1).

Some of the more traditional vehicles include the Aerial Regional-scale Environmental Surveyor (ARES)\(^\text{14}\), the Mars Gashopper, Mars Helicopter, freely falling concepts\(^\text{15}\), and Mars balloons\(^\text{16,17}\). Insect-inspired lift production has also been considered to achieve flight on Mars. Two of the most prominent examples are the Entomopter\(^\text{18,19}\), a flapping wing vehicle that uses a blown wing concept for lift enhancement, and the Solid State Aircraft\(^\text{20}\), a solar-powered flapping wing aircraft that employs recent advancements in material science. Both the Entomopter and the Solid State Aircraft designs are scaled-up versions of insects, but, it is not clear whether or not these designs preserved dynamic similarity with insects on Earth, thus it is unclear
whether the vehicles would have benefited from insect-inspired aerodynamic mechanisms. However, none of these designs have been fully realized, and the goal of flight on Mars is still an open problem.

Recently, a novel, dynamically scaled, bioinspired flapping wing aerospace architecture solution – a Marsbee, was developed. These Marsbees are bioinspired flapping wing vehicles that take advantage of the unsteady lift generating mechanisms found in low Reynolds number environments by conserving the relevant dimensionless parameters. Due to the extremely low density of the Martian atmosphere, a hovering Marsbee operates in a Reynolds number range of $100 < Re < 5000$, similar to the range of Reynolds numbers encompassed by hovering fruit flies, crane flies, bumblebees, hummingbirds, etc. on Earth.

Because of their small size and light weight, a data gathering mission could be accomplished using a large number of Marsbees to provide a reconfigurable and resilient swarm of flying vehicles in combination with a rover. Marsbees could carry a variety of different sensors capable of a wide range of tasks from taking atmospheric readings to recording land topography. This could supplement a rover’s traditionally limited view of the surrounding landscape and allow for more informed choices about direction of travel. An additional advantage of a fleet of Marsbees is that when one fails, another unit can take over its task or a new unit can be added to the active swarm from the reserve. This has the potential to dramatically increase mission duration and the overall system life cycle. For the much larger Mars Helicopter (blade diameter $\sim 1.2$ m), when the single unit fails, the mission is permanently ended or postponed until the unlikely event that the unit can be repaired, or a new vehicle is sent on the next Mars mission.
1.4 **Objective**

The main objective of this thesis is to experimentally test the hypothesis that bioinspired flight mechanisms can produce sufficient lift to fly on Mars via a physical, robotic Marsbee. As such, a Marsbee prototype is designed with wings and kinematics based on earlier numerical solutions\textsuperscript{22}. The Marsbee is then placed in a variable pressure chamber, where the air density is reduced to the Martian density level of \(1.42 \times 10^{-2}\) kg/m\(^3\). Aerodynamic forces and wing deformations are recorded at various flapping frequencies. The resulting forces and wing motions can be used to later inform and improve the computational models still being developed for flapping wing flight in Mars atmospheric conditions.

1.5 **Outline**

In Chapter 2, a literature study is described, discussing the current state of Mars exploration, prior Mars flight vehicle concepts, insect lift enhancement mechanisms, and prior flapping wing force measurements. In Chapter 3, the experimental methodology is covered, including the basic experimental setup, descriptions of the different vacuum chamber facilities used, as well as descriptions of the force transducer and optical tracking setup. In Chapter 4, results for both the force histories and wing deformation measurements are presented, and their implications are discussed. In Chapter 5, the conclusion is stated, and novel contributions are listed, the work left to future researchers is also stated.
CHAPTER 2

LITERATURE STUDY

In this literature study, three main topics will be covered. First, a summary history of Mars flight vehicle concepts is presented. This section discusses and compares numerous examples of Mars flyers that have been considered. Second, a summary of low Reynolds number lift enhancement mechanisms is presented. In this section, the benefits of flapping wing flight in the low $Re$ regime is discussed. Finally, the literature study will conclude with discussion of some methods used to record flight forces on flapping wings. This study helped to inform the experimental procedure by ensuring that it was consistent with how previous researchers had conducted their experiments.

2.1 Previous Mars Flight Concepts

Flight on Mars remains a desired, yet still unachieved, goal. In addition to allowing more detailed study of the Martian atmosphere, a reliable Mars flight vehicle could be used to guide rovers and supplement orbital imaging with more detailed local terrain mapping. This would allow for the valuable rover time to be used in the most fruitful way possible, virtually eliminating instances where the rover must back track to avoid obstacles or dangerous terrain. Furthermore, Mars flight vehicles can carry sensors
and wireless communication devices in combination with a Mars rover. These enhanced sensing and information gathering abilities can contribute to NASA’s Mars exploration objectives, including determining the habitability of Mars, obtaining surface weather measurements to validate global atmospheric models\textsuperscript{16}, and preparing for human exploration on Mars\textsuperscript{24}.

To date, no man-made device has flown on the red planet. NASA’s Jet Propulsion Laboratory has designed the Mars Helicopter which is slated to fly with the 2020 Mars rover. It is expected to arrive on Mars in early 2021. However, its capabilities are expected to be fairly limited with only 180 seconds of flight time per day\textsuperscript{23}. The Martian atmospheric density is only around 1\% that of Earth’s sea level density\textsuperscript{25}, and experimental studies of rotorcraft lift generation in low Reynolds number environments show reduced lift generation capability compared to what is possible on Earth, therefore rotorcraft are likely not the optimal solution to flight on Mars. Low lift coefficient achieved by rotary wing aircraft in low Reynolds number ranges means that the helicopter requires a large rotor\textsuperscript{23} and thus a large volume to transport it to Mars. This large volume requirement makes the Mars Helicopter an expensive solution to potential flight on Mars. Rotorcraft are further limited on Mars by the lower speed of sound, putting a cap on the maximum blade diameter and speed of rotation to avoid adverse compressibility effects at blade tips. Despite this, another rotorcraft that was considered for Mars flight was the Mesicopter\textsuperscript{26}, a small 17 g quadrotor that sought to be a reusable flight vehicle similar to the Mars Helicopter.

The current state-of-the-art solution to Mars surface mapping relies exclusively on orbiters like the MRO. While this method is very good at covering large swaths of the
Martian surface in a very quick fashion, it is not ideal for rover support operations. The MRO’s HIRISE camera is capable of a minimum resolution of one meter at Martian ground level\(^4,8\). The relative lack of rover support has long driven a desire for flight on Mars, and many varied concepts have been put forward in an attempt to be the first to solve the problems associated with very low \(Re\) flight. Flight in \(Re\) regimes below \(10^5\) begins to encounter issues with low lift-to-drag ratios, and difficulty controlling the flight vehicle\(^8\).

Past Mars flight vehicle concepts are varied and interesting in their own right. The more traditional Mars flight concepts range from ARES, a traditional fixed wing aircraft powered by a bi-propellant rocket system\(^8,27\), to balloon type devices potentially capable of months of time aloft\(^28\). ARES\(^29\) is a rocket-powered, robotic airplane platform that was intended to aid the NASA Mars Exploration Program\(^14,30–34\). The prototype was designed to fly at Martian altitudes from 1 to 2 km and provide ground scan data to an orbiter that would then return to Earth. This would enable a larger amount of data to be returned than could be relayed through the Mars Reconnaissance Orbiter alone. Primarily due to the short 68 minute flight duration, the ARES system is limited in its ability to support a rover exploration mission. The ARES design does not permit landing on the Martian surface, and it is assumed that the vehicle will cease transmission of data when it impacts the Martian surface.

Many more traditional fliers have also been proposed for achieving Mars flight. The Airplane for Mars Exploration (AME) was a propeller driven concept designed primarily as a testbed for the deployment of a complex folded aircraft design\(^35\). It would have been single use, air deployed, and lost upon landing. These designs tend to have
longer flight times, but at the cost of only having a single flight. This limitation is shared across all of the fixed wing aircraft shown in Figure 2.1. This includes designs like the Astroplane, Canyon Flyer, Mars Flyer, Minerva, and Argo VII\textsuperscript{35}.

The Mars balloons could be used for long term detailed study of the Martian atmosphere, including the use of advanced meteorological sensors that could potentially yield a much greater understanding of Mars’s atmospheric makeup and Martian weather patterns. Some of the instruments suggested for the balloons include sounding radar that could allow for 3-D mapping of the Martian surface, anemometers for quantifying Martian high altitude wind patterns, and magnetometers that could shed light on how much of the Martian magnetic field remains intact\textsuperscript{16}. The latter is of particular importance to the future human colonization of Mars, as areas with a relatively strong magnetic field would provide some protection to astronauts from intense solar radiation present on the Martian surface. The super pressure balloons have been demonstrated at 30 km altitude on Earth, in densities that approximate those at 5 to 6 km in the Martian atmosphere\textsuperscript{16}. However, they are uncontrolled, and thus, limited in the scope of supplementing rover operations.

Many nonconventional fliers have also been considered for use on Mars. One such concept is the Mars Gashopper. The Gashopper was a concept for a robust Mars flight vehicle that used CO\textsubscript{2} propellant to enhance mobility\textsuperscript{36}. The Gashopper would combine surface and low altitude exploration to provide detailed information about large areas relatively quickly. The vehicle could also make use of in situ CO\textsubscript{2} to refuel mid-mission.
In an attempt to explicitly tackle the issue of the low-density atmosphere, freely falling concepts\textsuperscript{15} have also been proposed. These concepts take inspiration from Maple seeds that fall and auto rotate\textsuperscript{8,37} allowing them to take advantage of the additional lift generated by such configurations at low $Re$. These devices would be able to take advantage of the enhanced lift provided by a strong Leading Edge Vortex (LEV) similarly to their inspiration on Earth\textsuperscript{38} (see also Section 2.2).

One of the more unusual concepts for Mars exploration comes in the form of the Cannon Assisted Flying Exploration (CAFE) system. This system would use a CO$_2$ cannon to launch flight vehicles into the Martian atmosphere\textsuperscript{8}. Once deployed the aircraft would scan an area of the Martian surface. The flier would necessarily be very lightweight and limited in capability.

Insect-inspired lift production has also been considered to achieve flight on Mars. The Entomopter\textsuperscript{18,39} is a flapping wing vehicle that uses a blown wing concept for lift enhancement. The Solid State Aircraft\textsuperscript{40} is a solar-powered flapping wing aircraft that employs recent advancements in material science. This prior research in bio-inspired flight on Mars employed simplified aerodynamic tools that could not accurately predict the complex, unsteady flow resulting from flapping wing motion\textsuperscript{18,39}. Due to the inaccuracy of these simplified models, the Entomopter required an additional vortex generator to augment the unsteady lift. In general these platforms seek to retain at least some of the characteristics of natural fliers on Earth, often mimicking certain characteristics like wing flexibility\textsuperscript{8}. Most importantly, none of these designs have been realized and thus the goal of flight on Mars is still an open problem.
Table 2-1. Characteristics of previous Mars flight concepts and selected insects with wing loadings presented in Martian N. Flight times are estimated by the researchers who proposed each concept. Asterisk on flight time denotes single use vehicle. Daggar on wing area indicates rotary wing disk area.

<table>
<thead>
<tr>
<th>System</th>
<th>Wing Span (m)</th>
<th>Wing Area (m²)</th>
<th>Mass (kg)</th>
<th>Wing Loading (N/m²)</th>
<th>Flight time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AME      35</td>
<td>12.44</td>
<td>12.24</td>
<td>203.8</td>
<td>61.8</td>
<td>528*</td>
</tr>
<tr>
<td>Minerva 35</td>
<td>6.18</td>
<td>6.675</td>
<td>141.5</td>
<td>78.7</td>
<td>75*</td>
</tr>
<tr>
<td>Mesicopter 36</td>
<td></td>
<td>4.908e-4</td>
<td>0.017</td>
<td>31.1</td>
<td></td>
</tr>
<tr>
<td>ARES    35</td>
<td>6.33</td>
<td>7.11</td>
<td>157</td>
<td>81.94</td>
<td>68</td>
</tr>
<tr>
<td>Argo VII 35</td>
<td>6.66</td>
<td>7.34</td>
<td>164</td>
<td>82.9</td>
<td>87*</td>
</tr>
<tr>
<td>Astroplane 35</td>
<td>21</td>
<td>20</td>
<td>300</td>
<td>55.7</td>
<td>600*</td>
</tr>
<tr>
<td>Canyon Flyer 35</td>
<td>2.2</td>
<td>.77</td>
<td>14.6</td>
<td>70.4</td>
<td>15*</td>
</tr>
<tr>
<td>Mars Flyer 35</td>
<td>1.562</td>
<td>0.63</td>
<td>12</td>
<td>70.7</td>
<td>20*</td>
</tr>
<tr>
<td>Entomopter 18</td>
<td>1.0</td>
<td>0.170</td>
<td>1.01</td>
<td>13.18</td>
<td>10</td>
</tr>
<tr>
<td>Mars Helicopter</td>
<td>1.1</td>
<td>0.95³</td>
<td>1.8</td>
<td>7.03</td>
<td>3</td>
</tr>
<tr>
<td>Hoverfly 41</td>
<td>0.0167</td>
<td>16.47e-6</td>
<td>16.6e-6</td>
<td>1.01</td>
<td></td>
</tr>
<tr>
<td>Fruit Fly 42</td>
<td>0.006</td>
<td>1.6e-6</td>
<td>1.02e-6</td>
<td>2.36</td>
<td></td>
</tr>
<tr>
<td>Monarch butterfly 43</td>
<td>0.01</td>
<td>26.05e-4</td>
<td>0.00042</td>
<td>0.598</td>
<td>600</td>
</tr>
<tr>
<td>Hawkmoth 43</td>
<td>0.185</td>
<td>0.0079</td>
<td>0.011</td>
<td>1.41</td>
<td>360</td>
</tr>
<tr>
<td>Cicada 44-46</td>
<td>0.10</td>
<td>0.0012</td>
<td>0.0011</td>
<td>3.65</td>
<td>16.7</td>
</tr>
<tr>
<td>Bumblebee</td>
<td>0.028</td>
<td>1.97e-4</td>
<td>0.0005</td>
<td>9.42</td>
<td>88.9</td>
</tr>
<tr>
<td>Hummingbird 44</td>
<td>0.137</td>
<td>0.0029</td>
<td>0.011</td>
<td>14.1</td>
<td>1200</td>
</tr>
<tr>
<td>Marsbee</td>
<td>0.024</td>
<td>0.028</td>
<td>0.006</td>
<td>0.795</td>
<td>348</td>
</tr>
</tbody>
</table>
Figure 2.1. Plot of wing loading vs flight time data from Table 2-1. Some of the higher wing loading flyers are able to maintain a long flight endurance with a high aspect ratio. However, they come with the significant drawback of being single use, while Marsbees and Mars Helicopters are reusable. It is also clear that the significantly lower wing loading of an optimal Marsbee corresponds to a longer flight time.

2.2 Low Re Effects and Lift Enhancement

There are several benefits gained by using insect inspired flight for Martian exploration. First, in the low Reynolds number Martian flow regime, there exist several unsteady lift enhancement mechanisms\textsuperscript{47}. Insect-scale flapping wings are able to take advantage of these mechanisms in a way that the fixed wing or rotary wing concepts cannot.

One of the first unsteady lift enhancement mechanisms to be discovered was the “clap and fling” mechanism\textsuperscript{48}. This mechanism is especially important in small species. It
is due to the wing interaction that occurs when the wings come together at the top of their stroke and “clap”, then begin their downstroke and “fling.” This interaction helps to set up a circulation during the rest of the downstroke. The clap-and-fling mechanism has been previously observed by Liu\(^8\) using a high speed camera shooting at 1000 frames per second. Liu theorizes that the clap-and-fling mechanism may help to avoid unfavorable phase delay during stroke reversal.

Another important unsteady lift enhancement mechanism is the delayed stall\(^{47,48}\). In this mechanism, a flow structure forms at the leading edge of the wing, which is characterized by high vorticity and a region of low pressure. Depending on the kinematics of flapping wings, this LEV can be stabilized for example by spanwise fluid flow\(^{49}\), yielding additional lift throughout the stroke\(^{48}\). The LEV is a very powerful aerodynamic mechanism that is present in other flyers such as plant seeds\(^{37}\), larger flappers such as birds\(^{50}\), and even large delta wing aircraft\(^{51}\). The LEV is known to be a very important contributor to low \(Re\) flapping wing lift generation. Though it is seen on some larger systems, the LEV tends to break down faster at higher \(Re\)^\(^{52}\), making it more useful at the scale of insects. This stability of the LEV is still an on-going research topic.

Another important insect flight characteristic is wing rotation. In their study Dickinson et al.\(^{48}\) found two force peaks at the end of an insect’s wing stroke. The first of which they liken to the Magnus effect. They theorize that the lift is generated due to an induced circulation that lowers the pressure on one side of the wing thereby causing an additional lift force. They tested their theory and observed that if the wing rotation timing was not in phase properly with the stroke reversal then the force would disappear or produce a downward vector. The second component was contributed to wake capture.
Wake capture is another important force augmenter in hovering insect flight. First, it allows the wing to be positioned properly for the beginning of the stroke reversal so that it can produce lift on the next phase of the stroke. Depending on the amplitude and phase of the wing rotation, the wing can further benefit from the wake in the flow field\textsuperscript{48}. This wake capture mechanism allows the fluid velocity generated by the end of a previous stroke to be captured and used to generate extra lift by the following stroke\textsuperscript{53}. In order to test the effects of wing rotation on insect flight Dickinson et al.\textsuperscript{48} ran a series of tests using a dynamically scaled fruit fly model with a force sensor at the root of one wing to record the time history of the forces acting on the wing. The wings were attached to a mechanical actuator as shown in Figure 2.2.

![Figure 2.2. Experimental setup used by Dickinson\textsuperscript{48}. The wings are submerged in a vat of mineral oil and the forces are recorded. They had control of the wing rotation and could set it to be either advanced, symmetric, or delayed relative to the flapping cycle.](image)

They found that the wing rotation was a key factor in the augmented lift generation seen in insects. The lift measured in their experiment was around 500 mN.
The wing rotation mechanism, when timed correctly, was able to generate lift well in excess of the delayed stall mechanism alone. They also found that wake capture led to the generation of lift for several hundred milliseconds after the end of a wing translation. The wake capture is dependent on wing rotation, with an advanced rotation leading to a positive lift force post translation, and a delayed rotation leading to a negative lift generation.

The clap and fling, delayed stall, rotational lift, and wake capture mechanisms are unique unsteady lift-enhancement mechanisms present in flapping wings at low Reynolds number ranges that enable insects to generate far more lift than can be generated by their wings in a steady state flow condition. Pohly et al.\textsuperscript{22} show that a dynamically scaled, bioinspired flapper with a 5g mass could hover on Mars by taking advantage of these effects. They show in Figure 2.3 the LEV remaining attached to the wing throughout the downstroke.

![Figure 2.3. Illustration by Pohly et al.\textsuperscript{22} showing a bioinspired flapper in Martian atmospheric conditions. The vorticity shown is based on a 3D Navier Stokes solver for a single wing. The second wing and body are used for illustration purposes only.](image-url)
2.3 Previous Flapping Wing Force Measurements

There are several common methods used to record forces on flapping wing fliers. The methods are highly varied and range from force measurement on dynamically scaled models\textsuperscript{49,54} to direct tethered force measurements and reconstruction of forces from high speed video\textsuperscript{54} or motion tracking cameras\textsuperscript{55}. Each method comes with its own set of advantages and drawbacks which will be discussed in the following paragraphs.

One non-intrusive form of flight force measurement uses multiple high speed cameras mounted orthogonally to one another in order to allow researchers to reconstruct the flight mechanics by using the three different views of the freely flying animal\textsuperscript{54}. This method has the advantage of being completely non-intrusive because it does not require tethering the animal or using reflective markers on the creature’s wings. The flight forces can be estimated based on the flight dynamics equations. However, it does have the major drawback of a very small capture volume, making it unsuitable for measuring motions of relatively large flyers.

Insect flight force measurements also take more intrusive forms. The least intrusive of these is the use of motion tracking cameras to record the 3D positions of multiple retroreflective markers on the animal’s wings. From this method, Kang et al.\textsuperscript{55} were able to calculate the lift for climbing flight in Monarch butterflies. This method has the disadvantage of requiring reflective markers be attached to the animal’s wings, the markers add mass, and possibly influence flapping behavior. However, the interplay between the measured wing motion and forces can be studied for free flight in a large capture volume.
The most intrusive flight force measurement method is tethered force measurements. They provide excellent direct force measurements, and can use highly sensitive sensors; however, the tether provides an unnatural sensory stimulation and causes the animal to behave differently than it would in free flight. It is shown by Fry\textsuperscript{54} that the lift contribution of translational forces in freely flying insects is around 80\%, where previous experiments on tethered insects performed by Dickinson et al.\textsuperscript{48} found the translational component to be approximately 65\% of the insect’s lift generation.

Despite its drawbacks, many insect aerodynamic force measurements are conducted with tethered flight. One common kind of tether used in testing of robotic flappers is employed by Wu et al.\textsuperscript{44} In their tether, two flapping wings and their actuator are supported by a load cell. The setup allows for free movement of the wings while also providing adequate thrust measurements. The forces were measured by use of an ATI Nano-17 force transducer. Their test was on the effect of wing stiffness when relating to thrust. They found that the stiffest wings produced the lowest thrust. Another type of tether is used by Singh and Chapra\textsuperscript{56}. Their experimental setup was similar to that used by Wu et al. except that it measured the forces generated by the wing through a force transducer mounted at the wing root. Their experimental goal was to validate an aerodynamic model that could better predict lift and other forces based on the wing kinematics. The forces measured were in to 60 mN range.

Another research group that recorded flapping wing force measurements is that of Agrawal and Agrawal\textsuperscript{57}. They mounted a flapping wing on an ATI force transducer and recorded forces at a sampling frequency of 1000 Hz. The flapping motion and the rotational motion of the wing were both controlled by a separate motor. The flapping
frequency was 26 Hz, and they measured a lift of 1.17 g for a rigid wing and 1.13 g for a flexible with an angle of attack of 50 deg. The observed trend in their data, which was recorded at 30, 40 and 50 deg angles of attack, was that while a rigid wing generated a higher peak lift, the flexible wing generated a consistent vertical lift force across a wider range of angles of attack. The flexible wing also consistently generated larger horizontal thrust forces than the rigid wing.
CHAPTER 3

METHODOLOGY

Based on previous numerical calculations\(^5\), we suspected that it is possible for a bioinspired flapping wing flight vehicle to fly in a Martian density environment. To confirm this theory, we placed the Marsbee flappers in a vacuum chamber while tethered to an ATI Nano 17Ti force transducer. We then recorded the lift generated at various frequencies so that if it was indeed possible for the Marsbee architecture to generate sufficient lift on Mars, we could determine what flapping frequency would be necessary, as well as any additional payload the system could carry.

Several factors contribute to lift generation with flapping wings. These include flapping frequency, \(f\), flapping amplitude, \(\Phi\), angle of attack, \(\alpha\), and wing area \(S\). Figure 3.1 shows the relevant quantities on a flapper. Because the flapper relied on passive pitching, there was no direct control over the pitch angle, and the flapping amplitude was likewise restrained by the gear mechanism, the main method of controlling the force produced was to change the flapping frequency \(f\).
Figure 3.1. Flapper shown with relevant parameters labeled. Flapping amplitude (Φ), wing pitch angle (α), wing span (R), chord (c), flapping frequency (f), leading (LE) and trailing (TE) edge. Force transducer axis orientations are also noted.

3.1 Power Supply

The power supply used in the experiment was a Tekpower TP3005P. The power supply is shown in Figure 3.2. At Earth conditions, we varied the input voltage to both flappers between 0.5 V and 2 V in 0.5 V increments and between 2 V to 2.6 V in 0.2 V increments. The input voltage for Martian conditions was varied between 0.8 V and 2.6 V in 0.2 V increments. The power supply was capable of adjusting the supplied voltage between 0 and 30 V with current of 1.0 amp, in a minimum increment of 0.01 V. The flapper motor was limited to a maximum of 3.7 V and 1 amp, so the power supply was able to supply more power than was necessary.
3.2 Flapper Configurations

Two flappers were used during the course of the experiment. The first flapper, the Modified Chiba flapper, was based on a hummingbird-inspired flapper from Chiba University\textsuperscript{58} (Chiba flapper, Figure 3.3). The second flapper was the Marsbee prototype flapper that was selected to overcome issues encountered when testing with the Modified Chiba flapper. In both cases, the wing size and the flapping kinematics were modified to coincide with a prior numerical solution\textsuperscript{22}. It predicted lift that can offset the weight of a 6 g flapping wing vehicle, similar to the Marsbee robotic prototype.

The target flapping frequency was 30 Hz when in the Martian density environment of $1.42\times10^{-2}$ kg/m$^3$, based on the work of Bluman et al\textsuperscript{6}. Sizing of the flapper wing was based on a numerical solution that predicted a 6g flapper could hover on Mars with a 54 deg flapping amplitude, a 20 Hz flapping frequency, and a single wing...
area of 0.0035 m². The wing area on the Marsbee flapper was sized to double the numerical wing area due to its restrained flapping amplitude of 35 degrees for the upper wings and 30 degrees for the lower wings.

The Marsbee prototype flapper used a wing planform with a 0.065m maximum chord length and a span of 0.12m. The flapper gearing (Section 3.2) allowed it to take advantage of a high-speed motor, allowing for the RPM to be converted to torque. The experimental procedure was as follows. First, the flapper was mounted in the vacuum chamber, then the atmosphere was reduced to Mars density. The flapper was then run through a testing sequence. The power supply was set to supply constant voltage with a maximum current draw of 1.2 A. The voltage was increased from its starting point at 0.5 V in small increments to 2.6 V with a brief cool down period between tests to prevent motor overheating and burnout. The forces and wing motion were recorded at each voltage increment and saved for later post processing.

3.1.1 Modified Chiba Flapper

The modified Chiba flapper was tested in the Large Vacuum Test Facility (LVTF, Figure 3.4) at The University of Alabama in Huntsville’s (UAH) Propulsion Research Center (PRC). This flapper was used to demonstrate the unusual fluid-structure interaction (FSI) that arose with enlarged wings at flapping in a low density environment. Forces were not recorded using the Modified Chiba flapper due to its high intensity vibration causing saturation of the force transducer.
The LVTF has a test section with a diameter of 1.8 m and a length of 4 m. Similar to the PERL chamber, the LVTF uses a convection vacuum gauge sensor (InstruTech CVG101 Worker Bee) and is capable of very low vacuum including the pressure and density levels required for simulating Mars atmospheric conditions (1.42×10⁻² kg/m³). This chamber was not used in further testing due to the lack of a viewing port that was adequate for the use of Vicon cameras.
The initial test setup is shown in Figure 3.4. The Modified Chiba flapper was mounted on an 8.5 cm pedestal over the force transducer and secured in place with a spring loaded clip. The wires from the power supply to the flapper were taped below the force transducer mount to avoid their weight resting on the force transducer and possibly skewing the measurements. The wing size and the flapping kinematics are modified to coincide with a prior numerical solution\textsuperscript{22} that predicted a lift that can offset a 6 g flapping wing vehicle that is similar to the Marsbee robotic prototype. Based on the work of Bluman et al\textsuperscript{6}, the target flapping frequency was determined to be 30 Hz when in the Martian density environment of $1.42\times10^{-2}$ kg/m\textsuperscript{3}.

Because the Chiba flapper uses four wings, the wing size is based on doubling the total wing area of the previous computational results for a 6-gram, two-wing flapper configuration\textsuperscript{22}. The peak-to-peak flapping amplitude of the upper set of wings is kinematically restricted to $\Phi_u \cong 60$ deg and to $\Phi_l \cong 50$ deg for the lower pair of wings. Each of the four Marsbee wings has a single wing planform area of $S=0.0070$ m\textsuperscript{2} with a wing length of $R=12$ cm and mean chord of $c=5.5$ cm, resulting in a single-wing aspect ratio of $AR=2$. The two-fold increase in wing span from the baseline Chiba flapper, the increased wing area, and the resulting increase of inertial forces on the flapping mechanism led to the flapping frequency being restricted to $f < 10$ Hz. This frequency was far too low to provide sufficient lift in the Martian environment.

Visual inspection of the wing motion suggested that the relatively large Marsbee wings in the Martian density condition deform in a way that is qualitatively different than in the Earth density condition. Because the prototype flapper’s wing structure is based on
designs for flying on Earth, the fluid-structure interaction is accordingly optimized for the Earth density condition. Similar to the wing motion of flying insects\textsuperscript{11}, the wings passively pitch with the trailing edge of the wing following the wing’s leading edge. However, in Martian conditions where the density is about 1\% that of Earth’s, the resulting fluid-structure interaction is qualitatively different. The trailing edge of the wing leads in front of the leading edge (Figure 4.6 and Figure 3.10), resulting in the wing motion in the opposite direction of what insects produce.

3.1.2 Marsbee Prototype

The Marsbee prototype preserved the wing area (0.028 m\textsuperscript{2}) and span (0.12 m) from the Modified Chiba flapper, but the peak-to-peak flapping amplitude was lower. However, the gear system used a lower ratio and allowed the flapper to better take advantage of the motor speed. This led to a flapping frequency of nearly 20 Hz being achievable. There were two modifications to the wing design from the Modified Chiba flapper. The first design change was replacing the 0.5 mm wing spar with a 1.0 mm wing spar that mounted into the flapping mechanism more deeply to prevent the wing spar breaking loose at the root. The second design change was to the wing planform. Because of the design of the gearbox, the left and right wings could not be mounted as a single continuous unit across the width of the flapper. To ensure that the wings were not warped by the slight asymmetry in the mechanism, they were cut in half and separately glued to their respective wing spars. To prevent large passive deformations of the wing membrane due to the aerodynamic and inertial loads, the wings were taped to the fuselage at approximately three-fourths of the root-chord from the leading edge. They were also
taped across the tail spar of the so that the left and right sides were connected (Figure 3.5).

![Figure 3.5. Marsbee prototype. The wing spars are reinforced at the root due to the large inertial and aerodynamic loads causing structural failure at the wing root.](image)

Kinematically, the Marsbee prototype flapper was restricted to a flapping amplitude of $\Phi_u \cong 35$ deg and to $\Phi_l \cong 30$ deg, much less than that of the Modified Chiba flapper, and also less than the numerical solution. The numerical solution was a 6g, two wing flapper with a flapping amplitude of 54 deg and a flapping frequency of 20 Hz. The motor was a small, high performance quad copter motor (BetaFPV). It could accept a maximum of 3.7 V with a maximum speed of 93,000 RPM unloaded. The motor drove the flapping mechanism through the gearbox shown in Figure 3.5. The gear reduction ratio was 19.75:1, meaning that the maximum theoretical unloaded flapping frequency was 78.5 Hz. A pushrod was pinned to the final drive gear and allowed for the rotational motion of the motor to translate to linear motion that drove the flapper arms. The flapper arms were pinned at their center and each held one top and the opposite bottom wing. No battery or tail controls were included on the test article. None of the flapper mass was
offset in order to simulate Mars gravity. The projected full mass with battery and tail is 7.0 g.

Table 3-1. Component mass breakdown for Marsbee prototype flapper as used in testing. The flapper did not have the added mass of a battery or a tail.

<table>
<thead>
<tr>
<th>Component</th>
<th>Mass (g)</th>
<th>Percent of Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gearbox</td>
<td>1.173</td>
<td>26.98%</td>
</tr>
<tr>
<td>Wings</td>
<td>1.224</td>
<td>28.16%</td>
</tr>
<tr>
<td>Motor</td>
<td>1.950</td>
<td>44.86%</td>
</tr>
<tr>
<td>Total</td>
<td>4.347</td>
<td>100%</td>
</tr>
</tbody>
</table>

3.3 Vacuum Test Facility

Due to the difficulty of incorporating the Vicon cameras into the test environment in the LVTF, testing of the Marsbee prototype flapper was performed at the UAH PRC’s Plasma and Electrodynamics Research Lab (PERL). The chamber was much smaller than the LVTF, with a diameter of 0.3 m and a length of 0.9 m. The final test setup is shown in Figure 3.6. The Marsbee prototype was tested in the PERL to take advantage of the faster pump down time and the large side window in the chamber.
Figure 3.6. Marsbee experimental setup in the smaller (PERL) vacuum chamber. a) Schematic of vacuum chamber and motion tracking cameras. b) Outside view of the vacuum chamber with the Vicon motion tracking cameras looking through the chamber’s side viewing window. c) Interior view of the vacuum chamber housing the Marsbee test stand.

The force transducer (Section 3.4) was a strain gauge type, and thus relied on small changes in resistance to measure the forces applied. Due to the sensitivity of the signal in the force transducer wire, and the inability of the interface power supply (IFPS) to withstand near vacuum conditions, a vacuum chamber feedthrough was modified to seal around the force transducer wire to allow the wire from the force transducer to pass from inside the vacuum chamber to the IFPS outside the chamber.

The feedthrough used was a 44.5 mm vacuum flange that had been modified with a segment of 19.1 mm inside diameter stainless steel pipe welded in the place of electrical feedthroughs. The feedthrough is pictured in Figure 3.7.
The feedthrough had an inside diameter that was just large enough for the connector from the force transducer to the IFPS (12 mm diameter) to fit through the inside. Once the wire was threaded through, and ensuring that the force transducer was on the side of the flange that faces into the chamber, a series of three 25.4 mm flat washers that had been modified with a cut from one edge to the middle were placed into the “outside” end of the feedthrough. The first washer was placed so that it was resting on the lip inside the threaded portion of the feedthrough, then a layer of silicone RTV gasket maker was spread over the first washer. Next, the second washer was placed on top of the layer of silicone with the cut facing the opposite direction of the cut in the first washer. Finally, another, much thicker layer of silicone was spread such that it filled the threaded portion of the flange completely. The final washer was pressed onto the top of the silicone to protect it from damage. The assembly was left to cure overnight. Once the silicone was cured, a layer of high vacuum grease was spread on the side of the feedthrough that would be exposed to the Martian density conditions.

The feedthrough was tested in the PERL vacuum chamber by reducing the pressure to 66.7 Pa and observing the pressure in the chamber after a 15-minute wait. Because the pressure had increased by approximately the same amount as the pressure in
the chamber with a blank flange installed in the same location, the feedthrough was deemed sufficient for vacuum use and was used in subsequent testing.

### 3.4 Force Transducer

The force measurement device used for this study was an ATI Nano 17 Titanium force transducer. The sensor was calibrated for a maximum loading of 8 N in the $x$ and $y$ directions and 14.1 N in the $z$ direction. The sensor had a resolution of 1.46 mN along all axes. The acceptable torque range was 50 N-mm about each axis with a resolution of 2.7 N-mm about the $x$ and $y$ axes, and 6.9 N-mm about the $z$ axis. The force transducer was connected through an ATI Interface Power Supply (IFPS) to a National Instruments Data Acquisition Device (DAQ) that communicated the recorded measurements to a PC through a USB connection. Before the start of each trial, the transducer was setup such that the load due to the flapper’s own weight was zeroed. The motion of the flapper was actuated by supplying a series of input voltages to the drive motor. For each trial, forces were recorded for five seconds. A low pass filter with a cutoff frequency of 100 Hz was used to condition the data gathered during the trials. The mean lift was calculated by time-averaging the force in the lift direction over the five second interval.

When testing, the transducer was held in place on an in house designed, 3D printed mount. The bottom of the force transducer was bolted to the upper half of the mount, and the lower half was bolted onto the test stand. A foam spacer was sandwiched between the upper and lower halves of the mount to insulate the force transducer from the vibration caused by the vacuum pump during the depressurization process. This mount is shown in Figure 3.8.
Figure 3.8. ATI force transducer, shown mounted on a custom 3D printed base. A foam layer was inserted between the upper and lower halves of the mount to insulate the force transducer from the vibrations caused by the vacuum chamber motor pumping.

Later in testing, the mounting was modified. The modification was a shorter pedestal above the force transducer. This was done to eliminate the errors encountered with the long moment arm causing an overload in one of the torque components, thus necessitating the entire test to be repeated to generate useful data. The second reason for lowering the height profile of the flapper mounting system was because the vacuum chamber had a diameter of only 0.3 m. This meant that the old mounting could not be used in its entirety because the flapper wings would impact the sides of the chamber if it was not suspended at the right height. The modified mount can be seen in Figure 3.6c. The mount had to be modified to account for the lack of a flat mounting surface in the round vacuum chamber. It also had to be adjustable enough to allow for repositioning of the flapper to ensure that the Vicon cameras could see all of the markers through the single window in the vacuum chamber.
To test the accuracy of the force transducer, a high precision digital balance was used to measure the masses of several calibration bodies. Each mass was in turn placed on the force transducer. The force exerted by each object was used to determine the object mass. The value of gravity assumed for this conversion was 9.81 m/s². Each measurement was repeated five times and averaged then compared to the values measured from the high precision balance. Table 3-2 lists the masses and percent differences from the known mass. The error percentages were deemed acceptable at approximately 3% of the mean in the 6 gram range. The standard deviation of the values recorded by the force transducer was consistently low and was likewise seen as acceptable. The 95% confidence interval for a small population was determined for each measurement.

Table 3-2. Known masses compared to masses measured by the force transducer along with percent differences. The standard deviation was calculated between the five measurements recorded using the force transducer.

<table>
<thead>
<tr>
<th>Known Mass (g)</th>
<th>Mean Measured Mass (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2706</td>
<td>0.286±0.0962</td>
</tr>
<tr>
<td>1.9253</td>
<td>1.77±0.75</td>
</tr>
<tr>
<td>3.9715</td>
<td>3.82±0.705</td>
</tr>
<tr>
<td>6.6500</td>
<td>6.45±0.657</td>
</tr>
<tr>
<td>31.703</td>
<td>31.69±1.07</td>
</tr>
<tr>
<td>51.858</td>
<td>51.82±0.75</td>
</tr>
</tbody>
</table>
3.5 Optical Wing Deformation Measurements

For wing deformation measurements, an optical tracking system was used. Nine small reflective tape markers were placed on one of the wings (D-L in Figure 3.9), with markers A, B, and C being placed on the mounting bracket used to secure the Marsbee to the force transducer. Because of this, markers A, B, and C were inserted digitally in Figure 3.9 in locations representing where they were relative to the flapper during testing. Markers A and B were used to form the flapper axis, with marker C serving as a third point to generate a reference plane. The 3D position of each marker was recorded using an array of Vicon T40s cameras placed outside of the small vacuum chamber (Figure 3.6a,b). Each reflective marker is 3×5 mm in size and weighs approximately 3.9×10⁻³ g. The total mass of all nine markers was around 9% of the mass of the individual wing. This method was previously used to measure the three-dimensional wing kinematics and the body motion of freely flying Monarch butterflies. Five Vicon cameras were positioned outside the chamber and calibrated such that the marker positions on the wing could be clearly recorded through a glass viewing window located on the side of the chamber. The marker distribution on the wing was chosen such that both chordwise deformation of the wing as well as the three-dimensional shape of the wing could be measured. In addition to the wing markers, two more markers (A and B in Figure 3.9) were placed on the flapper body as a reference line.
Figure 3.9. Position of the reflective markers on the Marsbee wing. Markers A, B, and C are shown in representative locations.

The wing flapping angle was determined using the position of markers A and G (Figure 3.9). The flapping frequency was obtained by taking the FFT of the time history of the flapping angle. The wing pitching angle was calculated as the angle between line joining G and I with respect to longitudinal axis of the flapper formed by markers A and B. The chordwise deformation of the wing was determined using the line connecting wing markers G and I. Marker H was ignored because the majority of the wing deflection occurred between markers H and I, with only minimal deflections in the segment from G to H. As a result of this, the data quality improved when the chord deflection was taken as a whole.

The experimental setup enables simultaneous measurements of flapping wing kinematics and the resulting time history of forces in Earth and Martian atmospheric density condition at various flapping frequencies. The wing motion was recorded at a sampling rate of 400 Hz and the forces were recorded at a sampling rate of 2000 Hz. Both the Marsbee flapper and the force transducer were located inside the chamber and powered using externally located power supply units. The force transducer output was
connected to a National Instruments Data Acquisition (DAQ) board and the measured data was saved to an external computer. Any gaps in the recorded marker position data were interpolated using cubic spline interpolation. The gaps in the data were always 5 frames or less with the maximum number of frames missing in a data set being 17, and making up roughly 22% of that run. Most of the data sets were missing only around 4% of their frames. The wing motion data were smoothed using a low pass filter with a cut off frequency of 50 Hz. The recorded force data, which included higher frequency oscillations, were filtered using a low pass filter with a cut off frequency of 100 Hz.

3.5.1 High Speed Video

For visualization purposes, the wing motion was recorded in the large vacuum chamber using a high-speed camera capable of shooting 960 frames per second. This allowed a qualitative understanding of the wing deformation at different densities and wing flapping frequencies. The flapper was mounted in the vacuum chamber as before, and was run through the same range of voltages, and thus frequencies, as during the optical motion tracking tests. This allowed for a visual verification of what was seen through the Vicon cameras. The high speed camera was capable of shooting 0.2 s per video capture, but when several captures were taken this allowed for the majority of a stroke to be captured.
Figure 3.10. Snapshots of the wing and passive pitch motion in a) ambient Earth and b) Martian atmospheric conditions. In the ambient Earth density condition, the trailing edge follows the leading edge as the pairs of upper and lower wings come together, similar to insect wing motions. However, the trailing edge leads the leading edge in the Martian density condition.

The main highlight is that in the ambient Earth conditions, the pitching motion mimics the pitching motion of flexible wing insects, namely in the way that the trailing edge lags behind the leading edge for each wing stroke. As seen in Figure 4.7, the “clap and fling” mechanism\textsuperscript{47,48} was also observed at the stroke ends.

However, in the low-density Martian environment, during some strokes, the pitching motion can be opposite of what is desired – i.e. the trailing edge can precede the leading edge, resulting in the aerodynamic forces being generated in undesired directions. Specifically, at 30% of the flapping period when the upper and lower wings are coming together, the Earth density condition (Figure 3.10a) is characterized by the leading edges coming together first, followed by the trailing edges of the wings (qualitative demonstration of the clap and fling mechanism). However, during the corresponding part
of the stroke in the Martian density condition (Figure 3.10b), the trailing edge of the upper wing is coming together with a nearly ‘flat’ lower wing, followed by the leading edge of the upper wing meeting the lower wing, resulting in low-lift-producing motion.
CHAPTER 4

RESULTS AND DISCUSSION

The forces and wing motion of the flapper were first recorded at Earth atmospheric density condition inside the PERL chamber, followed by Martian density condition as described in Section 3.4. The density inside the chamber was controlled by changing the pressure and recording the temperature. At Earth conditions, the temperature and pressure inside the chamber were 23º C and 99325 Pa, respectively, resulting in an air density of 1.2 kg/m³. At simulated Martian density, the temperature inside the chamber was 23º C for all tests. We varied the pressure between 1133.4 Pa and 1333.2 Pa, resulting in an air density between 1.333×10⁻² kg/m³ and 1.568×10⁻² kg/m³ during the tests, which is within the Martian atmospheric density range⁹,²³,²⁵.

4.1 Inertial Force Separation

We followed a well-documented procedure to separate the inertial force from the aerodynamic force⁴⁴. This was required to ensure that the forces read by the force transducer are a result of aerodynamic forces acting on the wing instead of inertial forces due to the motion of the wing mass attached to the force transducer. To perform this
measurement, the vacuum chamber was brought to a near-vacuum level of \( O(10^{-1}) \) Pa. The flapper was placed on the force transducer and forces were averaged over multiple flapping periods for a large range of flapping frequencies. The mean resultant forces are shown in Figure 4.1. The inertial forces generated by the flapping motion in near vacuum are an order of magnitude lower at \( O(10^0) \) mN compared to the mean aerodynamic forces at \( O(10^1) \) mN. This implies that the forces shown in Figure 4.2 are aerodynamic, and not inertial in nature. Thereby meaning that measurable lift is being generated.

![Figure 4.1](image)

**Figure. 4.1.** Experimental measurements as a function of flapping frequency at simulated Martian atmospheric conditions and near vacuum. The mean lift for both cases is normalized by 3.26 m/s\(^2\).

### 4.2 Lift Force Measurements

The wing motion and forces generated by the flapper were recorded over a range of input voltages. At Earth conditions, the input voltage to the flapper was varied between 0.5 V and 2 V in 0.5 V increments and between 2 V to 2.6 V in 0.2 V increments. The input voltage for Martian conditions was varied between 0.8 V and 2.6 V in 0.2 V increments. Three repeated measurements were acquired at each voltage.
Figure 4.2 shows the mean lift as a function of the flapping frequency based on three repeated measurements at Earth and Martian conditions. The Marsbee flapper generates positive lift in both conditions. The mean lift in Earth density condition (1.168 kg/m³) increases with the flapping frequency. The magnitude of lift (in grams) in Earth density condition, was around 11 g of lift at 17 Hz. The mean lift normalized with Martian gravity increases between 8 Hz and 14 Hz and then nonlinearly fluctuates with a maximum of around 8 g at 16 Hz, which is comparable with the lift observed when using the same wings in the Earth density condition. In Figure 4.2b, the lift trends for the flapper are normalized by their respective gravities. These results indicate that the Marsbee flapper at Martian conditions is capable of producing lift comparable to its weight. The uncertainty bars shown are based on the repeatability of the measured lift from three trials at each flapping frequency and in both density conditions.

Figure 4.2. Experimental measurements as a function of flapping frequency at Earth and simulated Martian atmospheric conditions. a) Measured lift in mN; b) Measured lift in grams. The mean lift at Earth and Martian densities are normalized with 9.8 m/s² and 3.26 m/s², respectively.
4.3 Wing Deformation Measurements

The mean lift trend in Figure 4.2 can be explained with the wing deformation measurements. A key mechanism in generating positive lift is the passive pitch angle resulting from wing deformation. This deformation is the result of a dynamic balance of the wing inertia, elastic restoring force, and aerodynamic force. For flexible wings, passive pitch angle plays the role of angle of attack. A pitch angle of 45 deg is known to produce the highest lift.\(^{48}\) The passive pitch angle is measured using the mean chord line and is relative to a plane formed by markers A, B, and C in Figure 3.9. The values shown in Figure 4.3 are for the mid-stroke.

![Figure 4.3. Comparison of passive pitch angle at Earth and Martian density conditions.](image)

For the Marsbee wing in Earth density condition, the mid-stroke passive pitch angle increases with flapping frequency, reaching 23 deg at 15 Hz (Figure 4.3). Therefore, the associated lift shown in Figure 4.2 generally increases with pitch angle. On the other hand, in Martian density condition, the wing deforms in a nonlinear way, producing a mean lift trend (Figure 4.2) that is qualitatively different than the trend in
Earth density condition. The trend of mean lift as a function of flapping frequency still appears to be similar to the passive pitch angle trend (Figure 4.2a and Figure 4.3). With an increase in frequency, the mid-stroke passive pitch angle remains nearly constant in the Mars conditions.

Figure 4.4 shows the phase delay between flapping and passive pitching. In the Earth density condition, the phase lag and the pitch angles increase with flapping frequency. Increased phase lag between the pitching angle and flapping is one of the key requirements for generating optimal lift for hovering wings. However, in the Mars density condition, phase delay decreases and even becomes negative at higher frequencies.

![Figure 4.4. Passive pitch phase delay vs wing flapping frequency. In the Earth density condition, the delay increases with flapping frequency. However in the Mars density condition, the phase delay decreases and even becomes negative at higher flapping frequencies, contributing to the inconsistent lift observed during the trials.](image)

In order to determine the relationship between the flapping frequency and the passive pitching frequency, an FFT of the time history of the $x$ component (see Figure
3.1) of the flapper wing markers G and I was taken. Data from the Earth density condition and Mars density condition were analyzed. The flapping frequency and the passive pitching frequency for several trials in each are listed in Table 4-1. The data presented is plotted in Figure 4.5.

Table 4-1. Flapping frequency and passive pitch frequency in Earth (1.168 kg/m³) and Mars density (1.42×10⁻² kg/m³) conditions.

<table>
<thead>
<tr>
<th>Test</th>
<th>Condition</th>
<th>Flapping Frequency (Hz)</th>
<th>Passive Pitch Frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Earth</td>
<td>4.5</td>
<td>1.9</td>
</tr>
<tr>
<td>6</td>
<td>Earth</td>
<td>5.8</td>
<td>5.8</td>
</tr>
<tr>
<td>7</td>
<td>Earth</td>
<td>9.7</td>
<td>8.3</td>
</tr>
<tr>
<td>8</td>
<td>Earth</td>
<td>12.6</td>
<td>12.6</td>
</tr>
<tr>
<td>42</td>
<td>Earth</td>
<td>12.9</td>
<td>12.4</td>
</tr>
<tr>
<td>48</td>
<td>Earth</td>
<td>14.8</td>
<td>14.1</td>
</tr>
<tr>
<td>13</td>
<td>Mars</td>
<td>9.4</td>
<td>19.2</td>
</tr>
<tr>
<td>14</td>
<td>Mars</td>
<td>11.62</td>
<td>23.64</td>
</tr>
<tr>
<td>15</td>
<td>Mars</td>
<td>12.9</td>
<td>10.7</td>
</tr>
<tr>
<td>17</td>
<td>Mars</td>
<td>14.3</td>
<td>29</td>
</tr>
<tr>
<td>26</td>
<td>Mars</td>
<td>15.4</td>
<td>14.4</td>
</tr>
<tr>
<td>29</td>
<td>Mars</td>
<td>16.5</td>
<td>31.2</td>
</tr>
<tr>
<td>32</td>
<td>Mars</td>
<td>18.9</td>
<td>7</td>
</tr>
</tbody>
</table>
Figure 4.5. Comparison of passive pitching frequency and flapping frequency in Earth density (1.168 kg/m³) and Mars density (1.42×10^{-2} kg/m³). The passive pitching frequency increases nearly linearly with flapping frequency in Earth conditions, but in Martian conditions, the passive pitch frequency is not consistent with the flapping frequency.

Figure 4.6 shows snapshots of wing mean chord pitch angle during a stroke cycle with a flapping frequency of 12.7 Hz in the Earth condition and 14.3 Hz in the Mars density condition. These two cases were chosen because they are similar in frequency but exhibit very different passive pitch deflections. In Earth density condition (Figure 4.6a), the trailing edge lags behind the leading edge, resulting in a motion that is similar to flying insects\textsuperscript{11}. This pitching motion produces high lift in an efficient manner. In Martian density condition (Figure 4.6b), the trailing edge leads the leading edge. This produces non-optimal lift. These contrasting pitch angle behaviors are consistent with the high-speed video wing snapshots in Figure 3.10.
Figure 4.6. Representative chordwise wing shape snapshots at a) Earth and b) Martian density condition.

4.4 Time Histories of Lift and Wing Deformation

Figure 4.7 shows the time history of wing kinematics and the corresponding force generation at Earth density conditions during three flapping periods for a representative trial at Earth density conditions. Figure 4.8 shows the same for a flapper in Martian density conditions, and exhibits the motion described in Section 4.3. The input voltage for this trial was 2 V and the flapping frequency was 12.9 Hz.

Figure 4.7a and Figure 4.8a show the flapping and pitching angles. The flapping amplitude was 38 deg. The pitching motion is slightly asymmetric during forward and backward strokes with a pitch amplitude 20 deg during the forward stroke and 18 deg during backward stroke. The backward stroke is slightly longer than the forward stroke. This type of nearly symmetric variation in passive pitch angle is typically observed in insect flight in hover\textsuperscript{41}. The wing motion shown in Figure 4.7a corresponds to a single wing of the flapper, however the lift generated shown in Figure 4.7b is the result of all four wings. The wing motion and lift were recorded simultaneously, and the data was synchronized using the largest positive force peak as the reference, since that point should theoretically mark the clap of the wings.
Figure 4.7. Comparison of experimentally measured wing kinematics and forces at 12.9 Hz in Earth density conditions. (a) Time history of flapping and pitching angles for three cycles. (b) Time history of lift. (c) Angle of wing chord during forward and backward stroke formed by markers G and I in Figure 3.9.

Figure 4.8. Comparison of experimentally measured wing kinematics and forces at 14.3 Hz in Martian density conditions. (a) Time history of flapping and pitching angles for three cycles. (b) Time history of lift. (c) Angle of wing chord during forward and backward stroke formed by markers G and I in Figure 3.9.
The time history of lift is shown in Figure 4.7b indicates that the lift in general is positive with a mean lift of 60 mN during three flapping cycles. The chord shapes formed by markers G and I (Figure 3.9) during forward and backward strokes are shown in Figure 4.7c. The dot represents the leading edge. The passive pitch angle due to wing deformation is nearly symmetric during forward and backward strokes which is consistent with the time history of pitching angle in Figure 4.7a. Additional discussion of the force components is located in Appendix A. As noted in Figure 3.1, the lift direction is assumed to be in the $z$ direction.

The wing kinematics corresponding to a representative flight at Martian density condition is shown in Figure 4.8. The input voltage for this trial was 1.4 V and the flapping frequency was 14.3 Hz (Table 4-1). The flapping angle is similar to the Earth density with slightly higher amplitude around 45 deg this increase in the flapping amplitude is likely attributed to larger spanwise wing deformations in the Martian density condition. However, the pitch angle time history is significantly different compared to the Earth density. The pitch angle amplitude is smaller and is asymmetric during forward and backward strokes. This indicates that nearly the same wing orientation is maintained during both forward and backward strokes. As seen in Table 4-1 and Figure 4.5, the pitching frequency in the Martian density is not as consistent and near the flapping frequency as it is in the Earth density. This also contributes to unfavorable motion and sub optimal lift generation. The variation of the time history of lift obtained from all four wings is closer zero with a mean lift of 24 mN over three flapping cycles. Figure 4.7c shows that the wing orientation is nearly the same during both forward and backward
stroke. Phase delay between the leading edge and trailing edge is necessary to ensure proper passive pitching motion.
CHAPTER 5

CONCLUSION

In summary, the resulting combination of the flapping and pitching motion is able to generate positive lift in the Martian density condition. However, the resulting pitch motion due to the large wings is not optimal, suggesting that bioinspired lift generation in Martian conditions can be improved by taking into account the fluid-structure interaction in the ultra-low Martian density condition. While the flapper was able to generate sufficient lift to offset its weight, it was producing much less than it theoretically could produce if the passive pitching and the phase delay were optimized for the Mars density environment.

5.1 Conclusion

In this study, we tested the hypothesis that a flapping wing aerospace architecture, Marsbee, was capable of generating lift beyond its weight in a Martian density condition using physical experiments. The Marsbee prototype flapper design was guided by a previous numerical solution that gave a target flapping frequency, amplitude, and wing area. Because the flapping amplitude and frequency were limited by the kinematics of the
flapping mechanism, the wing area was increased by a factor of two to compensate. We measured the forces generated by the Marsbee prototype in a Mars density environment. The force data was combined with wing deformation measurements and high speed video. In the experiment, a Marsbee flapper was mounted on a force transducer, and the forces generated by its flapping recorded. Simultaneously, one of the flapper wings was covered in a grid of reflective markers so that an optical tracking system could provide a quantitative depiction of the wing deformation during the force measurement. A high speed camera shooting at 960 frames per second was also used to verify qualitatively the wing deformation observed by the optical wing tracking. The experiment was performed in a vacuum chamber with the air evacuated until the density was in a representative Martian density range. The target density for the experiment was $1.42 \times 10^{-2}$ kg/m$^3$, the actual recorded densities ranged between $1.333 \times 10^{-2}$ kg/m$^3$ and $1.568 \times 10^{-2}$ kg/m$^3$. The motion of the wings when in the Martian density range was quantitatively different from their motion in Earth density.

For the study, the span of a single wing was 12 cm, with an average chord length of 5.5 cm and a maximum chord length of 6.5 cm, with an aspect ratio of 2. The wing area for each of the four wings was 0.007 m$^2$ for a total wing area of 0.028 m$^2$. The wings performed as expected on the upstroke, but, on the downstroke, they deformed in the opposite of the desired direction. This often led to the trailing edge being in advance of the leading edge of the wing, as seen in Figure 4.6b. This suboptimal wing deformation resulted in less lift being generated than is theoretically possible.

Nevertheless, the Marsbee flapper was experimentally shown to generate lift in excess of its weight, verifying the hypothesis. It was demonstrated that the flapper could
generate approximately 8-grams of lift while only weighing around 6-grams when flapping at 16 Hz. The lift trend, however, was not monotonically dependent with respect to flapping frequency. The lift generally increased in the Martian density when the frequency increased from 8-14 Hz, but at higher frequencies the trend became highly erratic, as seen in Figure 4.2. The wing passive pitch angle, shown in Figure 4.3, was less optimal in the Mars density condition than in the Earth density condition. In the Earth density condition, the passive pitch angle followed a consistent upward trend as frequency increased, while in the Martian density condition the passive pitch angle followed no discernable trend. Better understanding of the fluid-structure interaction could lead to vast improvements in lifting capability. The additional capability could also increase aerodynamic performance overall due to the more efficient optimal wing motion that could be generated.

5.2 Future Work

Future work on the Marsbee concept includes the following:

1) Development a better understanding of the fluid-structure interaction in extremely low density environments.

2) Characterize wing passive pitch behavior and design wings that are better suited to extremely low density. New wings could use active or passive pitching, or a combination of both to ensure that pitching is completed at optimal points in the stroke.

3) Fabrication of a Marsbee prototype based on the predicted numerical solutions. Prototype should be adjustable in flapping amplitude and be capable of mounting controls.
4) Tethered flight demonstration in Mars density condition.

5) Flight demonstration in simulated Mars atmosphere, rather than in Earth atmosphere at Mars atmospheric density.

6) Onboard power supply design and implementation

7) Derivation of a control scheme that will allow the flapper to fly untethered, eventually leading to an untethered flight in a simulated Martian environment.

5.3 Novel Contributions

This work has focused on proving aerodynamic models suggesting flapping wing flight on Mars is feasible. This work has made the following novel contributions:

1) Manufactured and modified Marsbee Prototype, and the mounting system used to suspend it while measurements were recorded.

2) Manufactured vacuum chamber feedthrough to allow force measurement in Mars density condition.

3) Used high speed camera to confirm suboptimal fluid-structure interaction.

4) Combined force measurements with optically tracked wing motion measurements, thereby furthering the understanding of the lift trends observed during testing.

5) Verified that flapping wing flight mechanisms can generate lift beyond their weight, thus validating the concept of a Marsbee.
APPENDIX A.

Filtered Force and Moment Data from Representative Trials

Force and moment diagrams presented below are taken from the data presented in Figure 4.7 and Figure 4.8. The filter used was a 6th order Butterworth with a cutoff frequency of 100 Hz. The force time history shown in Figure A.1 shows the three component forces in Earth density. The $x$ and $y$ components of the force are relatively symmetric about zero, but the $z$ component is positive consistently. This is also seen in Figure A.3, though the force component magnitudes are greatly reduced and less consistent. The average forces from Figure A.3 were taken over 3 flapping cycles. In the $x$ and $y$ directions, the average force was -0.70 and -0.22 mN, and the $z$ component average was 15.8 mN. The moments shown are relatively symmetric about zero, so are negligible over an entire flapping cycle. The relatively large magnitude of the moments can be attributed to the moment arm from the force transducer to the flapper. For these reasons, the lift force generated by the flapper is considered to be primarily the $z$ component.
Figure A.1. Force time history from the trial in Figure 4.7 in Earth density.

Figure A.2. Torque time history from the trial in Figure 4.7 in Earth density.
Figure A.3. Force time history from the trial in Figure 4.8 in Mars density.

Figure A.4. Torque time history from the trial in Figure 4.8 in Mars density.
REFERENCES

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