Design and Construction of an Experiment for the Investigation of the Effects of Gust on Flapping Wing Micro Air Vehicle Power Consumption

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In recent years, the promising nature of flapping wing flight has led researchers to investigate the wing morphology and unsteady wing aerodynamics found in insects to aid in the design of modern micro air vehicles (MAVs). A high-fidelity flapping wing MAV could achieve high mobility, hovering stability, increased stealth, and efficient flight at low speeds. These characteristics offer a viable solution to the operational requirements for the typical hazardous and dynamic environments encountered during flight. While the kinematics and morphology of flapping wings are well-understood, significant research has yet to be completed with respect to the control and power requirements necessary for reliable and repeatable operation in the transient conditions encountered during MAV flight. This paper explores initial experiments designed to test the power consumption necessary to maintain several wing beat frequencies at a variety of angles of attack and heading angles of a flapping wing MAV under simulated gust excitations. The test results will be used to quantify the performance of flapping wing flight as a function of various gust speeds and to aid in the design and evaluation of future models.

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
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<tbody>
<tr>
<td>f</td>
<td>wing beat frequency</td>
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<tr>
<td>α</td>
<td>angle of attack</td>
</tr>
<tr>
<td>φ</td>
<td>heading angle</td>
</tr>
<tr>
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</tr>
<tr>
<td>I</td>
<td>current</td>
</tr>
<tr>
<td>l</td>
<td>wing span</td>
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I. Introduction

Micro air vehicles (MAVs) are unmanned aeronautical robots with six degree of freedom mobility and are characterized as having multi-lateral dimensions less than 15 centimeters in length. In recent years, MAVs have been proposed for use in a number of potential applications including: reconnaissance, search and rescue operations, and hazardous chemical detection. For military implementation, they can easily be carried by small combat units in the field, reducing or eliminating their reliance on larger unmanned air vehicles, and increasing the team’s autonomy [1]. Because of their harsh operating environments and required maneuverability in confined spaces, such as caves or small buildings, micro air vehicles must be designed to provide high mobility, hovering stability, increased stealth, and efficient flight at variable speeds. Over the past 15 years, MAV research has primarily been aimed towards developing an understanding of the necessary aerodynamics, system design, and power systems required to produce operational vehicles. During this time, a vast number of MAVs have been created in the form of fixed-wing or rotary-wing models.

Fixed-wing MAVs are the easiest to design by scaling down the well-established design principles developed for larger commercial flight aircraft. Several of these models have been developed and operated by using their wings as lifting surfaces and relying on increasing the aerodynamic efficiency of the vehicle by maximizing the lift-to-drag ratio (L/D). However, due to their high flight speeds (typically from 6 to 10 m/s), lack of hovering ability, and poor maneuverability, fixed wing MAVs are only suitable for use in outdoor environments and reconnaissance applications [2]. Alternatively, research has focused on quad-rotor micro vehicles because of their hover, vertical take-off and landing (VTOL), and low speed operation capabilities. While rotary flyers are superior models for short range and indoor applications, rotary systems consume large amounts of power, generate significant noise, and may require complex control systems when multiple propellers are used for advanced maneuvers or stabilization under the dynamic conditions typical in flight [3].

Recently scientists have been asking the following: what innovative new micro air vehicle model can be used to achieve high mobility, variable flight speeds, and hovering stability with low power consumption and increased stealth? The answer lies not within innovation of a new concept, but within the fundamental nature of flapping wing flight found in birds and insects on Earth. Nature has had 3.8 billion years of evolutionary research and development to produce thousands of well-adapted solutions to efficient flight. For example, hummingbirds are highly mobile, generate lifting forces by rapidly oscillating their wings at a frequency of 12-90 Hz, which enables them to fly backwards, change directions swiftly, and fly upside-down for a limited period of time [4].

Moreover, numerous types of insects have been investigated due to their ample advantage over birds in mobility and hovering flight. For their size, insects can produce lift and thrust forces in flight 2 to 12 times their body weight [3]. Insect-like kinematics could provide an optimized solution to the flight of micro-scaled vehicles due to their demonstrated power/aerodynamic efficiencies and ability to complete a wide variety of flight maneuvers. In order to become the MAV model of choice for civilian and military applications, significant flapping wing vehicle research is left to be completed in the areas of autonomous and hovering flight, power sustainability, and reliable control throughout the potentially hazardous conditions encountered during operation, such as fires, airborne chemicals, or more importantly, wind gusts.

The challenge of maintaining stability and control under the influence of dynamic wind gusts remains to be explored in the realm of MAV research. In micro scale flight, the flow field is very sensitive to slight changes that could potentially cause disturbances in separation and turbulence. This paper explores the initial experiments designed to test the power consumption necessary to maintain several wing beat frequencies at a variety of angles of attack and heading angles of a flapping wing MAV under simulated gust excitations using a wind tunnel. The test results will be used to quantify the performance of flapping wing flight as a function of various gust speeds and to aid in the design and evaluation of future models reliable enough to operate under transient flight conditions.

Figure 1. Conceptualized dragonfly-inspired flapping wing micro air vehicle. [5]

American Institute of Aeronautics and Astronautics
II. State of the Art

The following section briefly outlines the most current understanding of the insect wing kinematics that produce the aerodynamic properties unexplained by the conventional quasi-steady flight assumption, allowing highly mobile and agile flapping wing flight. Additionally, information regarding current MAV power systems and the properties of gust are discussed.

A. Unsteady Aerodynamics

Due to their size and speed scales, flapping wing MAVs operate in the low Reynolds number regime, $10^4$ to $10^6$, in which there is a significant shift in the fundamental behavior of flight [6]. Relatively large forces and moments are encountered in this laminar dominant flow and lead to significant unsteady effects, proving to be substantially challenging in the development of aerodynamic, control, and power design. Contrary to steady-state theory used in typical fixed-wing aircraft, insects operate in a transient state and rely on the following four unsteady aerodynamic effects for lift production.

- Spiral leading edge vortex
- Clap and fling mechanism
- Rotational lift
- Wing-wake interactions

As air flows over the sharp leading edges of insect wings during a downstroke, it separates from the wing and rolls into a strong leading edge vortex (LEV) [7]. The vortex demonstrates a low pressure center that acts to pull the fluid along a circular path. Since this creates a region of low pressure above the wing, additional suction is provided which increases the lift of the wing. It seems that the wing would ultimately stall due to the continuous air flow feeding into the vortex, causing flow separation; however, the nature of the flapping motion causes a strong spanwise flow to mix with the LEV and produces a spiral leading edge vortex that flows towards the wingtip. This phenomena, shown in Fig. (2), helps stabilize lift production by siphoning off the vortex at the end of the downstroke and delaying the expected stall. The spiral LEV is the core mechanism insects use to generate lift.

The clap and fling mechanism, as seen in Fig. (3) below, begins with both of the wings ‘clapping’ or pressing together at the end of the upstroke. The wings then begin to ‘fling’ open, which consists of the wings separating at the leading edge and opening while rotating around the trailing edges. Following this motion, the trailing edges remain connected together until the included angle reaches close to $120^\circ$ [6]. As this happens, air is forced over the upper surfaces into the widening gap, creating a bound vortex around the wings [7]. The vortex generated by the clap and fling mechanism increases the air velocity over the upper surface while decreasing the velocity over the lower surface. Accordingly, this pressure gradient contributes to additional lift generation per Bernoulli’s theorem before the downstroke.

Recent approaches to studying biological flight have produced a myriad of slow-motion insect flight videos using high-speed digital cinematography. In these visualizations, it can be seen that insects rotate their wings about a span wise axis, which helps insects maintain a positive angle of attack during the downstroke and upstroke. A positive angle of attack allows flapping wing flyers to continuous lift production. Fig. (4) gives an appropriate illustration for the kinematics behind the wing rotation in insects.
The final unsteady mechanism found in insect flight is wing-wake interaction. Similar to wing-tip vortices found in commercial aircraft, wake vortices are generated near the end of an insect wing’s downstroke. Due to the rotation of the wing through the beginning of the upstroke, it is possible that the wing can intersect its own wake, capturing its energy to produce additional lift. The wake-wing interaction and the previously noted unsteady mechanisms, produce enough lift in micro-scale flight that would could not be predicted by steady-state airfoil theory. The next section explores how the structure of the insect aids in flapping wing flight.

B. Influence of Gust

Due to the unsteady nature of micro scale flight, the flow field is very sensitive to slight changes that could potentially cause disturbances in separation and turbulence. It should come as no surprise that the effects of wind gust within the atmospheric boundary layer (ABL) contribute significantly to the complexity in creating reliable power and control systems for flapping wing MAVs. The ABL is a region of the atmosphere extending from the ground to between 100 and 1000 meters, depending on the climate and terrain [10]. Based on the expected flight operations of MAVs, most vehicles will fly at low speeds relatively close to the ground and in urban environments, immersed in the lower portion of the ABL. It is within this region that aircraft encounter complex flows consisting of shears, recirculating eddies, vorticies, as well as mean winds that vary spatially and temporally [11]. A lightweight, reliable power source is necessary to supply the required energy for controlling and stabilizing a MAV in the dynamic flow conditions discussed.

C. Power Systems

High power and energy dense systems are vital for producing operational flapping wing MAVs. There are currently very few sources that are light enough and able to provide the power necessary even for steady flight conditions. A recent innovation, Harvard’s Robotic Fly in Fig. (5), uses a piezoelectric cantilever for powered actuation. Even though the device successfully delivers the required lifting forces, an inherent obstacle is that these devices require high voltage not available in current integrated power systems [12]. The Delfly, a large scale air vehicle pictured in Fig. (6) below, was produced by TU Delft and uses rechargeable Lithium Polymer batteries capable of an energy density of 130Wh/kg and a power density of 2600 W/kg on the micro scale [13]. The author has not encountered any research thus far focused on acquiring empirical data to quantify the effect of dynamic gust on flapping wing MAV power consumption. This paper aims to generate an analysis that will aid in the design and evaluation of future power systems reliable enough to operate under transient flight conditions.

Figure 4. Wing path for rotational lift. [7]

![Figure 4. Wing path for rotational lift.](image)

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Figure 5. Harvard’s piezoelectric robotic fly. [12]

![Figure 5. Harvard’s piezoelectric robotic fly.](image)

Figure 6. TU Delft Delfly micro vehicle. [13]

![Figure 6. TU Delft Delfly micro vehicle.](image)
III. Flapping Wing MAV Design

To begin the project, a basic flapping wing micro air vehicle was constructed using rapid prototyping and metal machining methods. The goal was to produce a prototype that could be mounted to a small wind tunnel and easily tested for power consumption. This section discusses the design of the first prototype and its properties.

A. Wing Morphology & Design

The goal for designing the wings to be used in the flapping wing MAV for experimentation was to create a wing that mimics the general morphology found in insects. Most fully developed insect wings maintain the same general structure, as seen in the Cicada wing in Fig. (7). Each wing is essentially a thin flap, with a sharp leading edge, connected via a hinge to the main body. For insects, a wing must be lightweight, yet stiff enough to remain aerodynamically efficient under loading [14]. The principle support of a wing membrane consists of a series of longitudinal veins connected by smaller cross veins. The veins act similar to cantilever beams, experiencing bending and twisting loads during operation. Also, the leading edge of the wing is often thicker than the support veins because it is the edge that travels through the air first and significantly influences the flow.

![Figure 7. Actual Cicada wings. [15]](image)

The prototype wings, shown in Fig. (8), were scaled to nearly twice the size of the actual Cicada wings and constructed using unidirectional carbon fiber rods with a 0.010” diameter and a 0.020” diameter for the support veins and leading edge spar, respectively. The material used for the wing membrane was Monokote plastic shrink wrap film. The general dimensions for the wings are listed in Fig. (8) and were designed with the required MAV dimensions in mind; additionally, the thickness of the wings was 0.025” and the mass per wing was 0.3g, typical measurements for a flapping wing MAV.

![Figure 8. Fabricated MAV wings.](image)

B. Flapping Mechanism

For initial experiments, the proposed flapping wing MAV will be designed to mimic oscillation of insect wings about the horizontal plane, but not the end-stroke rotation. Once the method for testing power consumption is analyzed and validated for a simple model, more complex MAV prototypes that fully capture the unsteady aerodynamics mechanisms can be developed for additional testing.

The mechanism generating the flapping motion is the simple cam system. The system linkages and main gear were designed in SolidWorks and created using a rapid prototyping machine. The mechanism is actuated using a micro DC motor and gear system. The entire MAV design is shown in Fig. (9). The micro DC motor was chosen for ease in testing power consumption; the setup for this is to be discussed in the Experimental Setup section of this paper.

![Figure 9. MAV Mechanism Design](image)
C. Wind Tunnel Mount

Since this project is concerned with testing the performance of the flapping wing MAV under the effects of gust, the prototype was designed for mounting purposes in a wind tunnel. A 4” mounting rod, connecting the MAV to a wind tunnel, was created by machining an aluminum rod with housing for the MAV motor. The mounting rod CAD design and prototype are pictured in Fig. (10) and Fig. (11), respectively. A hole was drilled through the portion of the rod that holds the motor, allowing for the motor’s electrical wires to be connected to an external power supply.

IV. Experimental Setup

An experimental setup was created to simulate a flapping wing MAV flying at speeds up to 10 m/s. The goal was to develop a system that could fix a prototype MAV at different pitch and heading angles under controlled air speed flows. This section of the paper outlines the components used and created to develop the setup.

A. Testing Environment

The 1’ x 1’ wind tunnel pictured in Fig. (12) was used to test the flapping wing vehicle at several speeds, up to a maximum speed of 10 m/s. The tunnel provides a 3’ test section where the MAV can be positioned with a mounting system. A power controller, Fig. (13), for setting the wind tunnel voltage sits within the rear wooden enclosure.

B. Speed Measurement

A pitot tube pressure sensor was mounted to the center of the wind tunnel test section (as seen in Fig. (14) on the next page) to test the incoming air flow speeds. The mount for the pitot tube, pictured in Fig. (15), was built using a rapid prototyping machine.
It is important to be able to set the air flow speed since empirical data will be collected relating various steady-state gust speeds to the power consumption, necessary to maintain several wing beat frequencies. For this reason, the pitot tube is connected to a pressure transducer that translates the dynamic pressure (in Torr) into a voltage signal. The signal is then processed using a portable data acquisition (DAQ) device and an analog input signal is sent to a LabView computer program. The electronics system and computer sit on a table in front of the wind tunnel. An overall system diagram is given in Fig. (16), and a block diagram of the LabView program is shown in Fig. (17).

Figure 16. System diagram of the electronics used in collecting wind tunnel air speed.

Figure 17. Block diagram of LabView program used to output the wind tunnel air speed.
The program created in LabView receives the input voltage signal, converts this into the original dynamic pressure collected from the pitot tube, and translates the pressure, \( q \) in units of Torr, to the velocity, \( v \) in units of m/s, using Bernoulli’s equation for dynamic pressure, Eq. (1) where \( \rho \) is the density in kg/m\(^3\).

\[
v = \sqrt{\frac{2q}{\rho}}
\]  

(1)

Once the pitot tube was calibrated at 0 velocity, wind speed data was collected at several applied power controller voltages for the wind tunnel. The data was then plotted, as seen in Fig. (18) below, and a linear regression line was fit to produce Eq. (2), which relates the input voltage (V) to the output air speed (m/s) of the wind tunnel.

\[
Velocity = 0.2017*Voltage - 1.6884
\]  

(2)

C. Electronic Speed Control

In order to streamline the data collection process and allow for future autonomous closed-feedback speed control, Eq. (2) from the regression line can be used in conjunction with a LabView program and microstepping driver to control a stepper motor. In turn, this motor will be connected to the wind tunnel power controller using a direct-drive shaft coupler. The dial on the power controller must first be removed to expose the control shaft. For example, a wind speed of 5 m/s would be entered into a LabView program that would in turn translate the stepper motor enough to rotate the power controller dial shaft to an approximate input voltage of 35 volts.

Fig. (19) depicts the design for the project’s speed control system. First, a polycarbonate hardware casing was constructed to house a microstepping driver and stepper motor, on the first and second levels, respectively. The driver and stepper motor will be connected using long wires to a power supply and the DAQ devices which sit with the electronic system near the wind tunnel test section. The direct-drive shaft coupler was built using a rapid prototyping machine; the coupler has drilled holes along each shaft for set screws to fix the shafts in place for smooth translation.
D. Micro Air Vehicle Mounting System

The goal of these initial experiments is to test the power consumption necessary to maintain several different wing beat frequencies at a variety of angles of attack and heading angles of a flapping wing MAV under simulated gust excitations. For this reason, a mounting system was developed such that the angle of attack and heading angle of the flapping wing prototype can be changed independently. The angle-change mechanisms and mounting supports were constructed using a rapid prototyping machine. The pitch and heading angle mechanisms have a range of $\pm 25^\circ$, these angles were embossed directly onto the part in printing. Also, the mounting system, shown in Fig. (20), is fixed to the top of the wind tunnel. The flapping wing MAV will face away from the mounting system, near the center of the test section so that the aerodynamic effects are not disrupted.

![System diagram of the wind tunnel mounting system for the MAV.](image)

With a flapping wing prototype, speed-controlled wind tunnel, and mounting system in place, the project is now able to test the power consumption of the MAV under various flight conditions discussed in the following section of the paper.

V. Testing and Results

At the time of paper submission, the flapping wing MAV is in the construction process, and the mounting system is being installed. This section discusses the methodology for data collection and the types of flight tests to be conducted. Results will be discussed at the AIAA Region IV Student Paper Conference on April 26, 2013.

A. Data Collection

An external power supply will be used to test the power consumption of the MAV. The electrical wires from the DC motor, that actuates the flapping wing MAV, will be fed through the hole drilled into the aluminum mounting rod. Accordingly, the wires will be secured along the pitch angle mechanism until exiting the top of the wind tunnel where the wires can then be connected to the power supply. During testing, the voltage and current levels required to maintain a certain wingbeat frequency under the current flight conditions can be recorded from the power supply system. Using the definition of electrical power, Eq. (3) can be used to determine the required power ($W$) using the voltage ($V$) and current ($A$) data.

$$P = VI$$

(3)
B. Flight Tests

Based on statistical data, a correlation exists between the wing beat frequency, \( f \) (Hz), and wing span, \( l \) (cm), of insects, given by Eq. (4) below [16]. Since the flapping wing made for the MAV prototype measures 7 cm in wing length, this corresponds to a wing beat frequency of approximately 0.375 Hz for steady state flight.

\[
ft^{1.15} = 3.54
\]  

(4)

The previous equation only gives the wing beat frequency associated with steady flight, but the flight tests conducted will be expanded to investigate higher flapping frequencies that may be encountered during take-off, landing, and agile flight maneuvers. The frequency of the flapping wing MAV during flight will be determined using a stroboscope tachometer. In addition, as stated previously, the effect of gust on power consumption will be evaluated by conducting experiments at several wind tunnel speeds, pitch angles (\( \alpha \)), and heading angles (\( \phi \)). Table 1 lists the various testing parameters involved in the experiment.

<table>
<thead>
<tr>
<th>Wing Beat Frequency (Hz)</th>
<th>Wind Tunnel Speed (m/s)</th>
<th>Pitch Angle (deg.)</th>
<th>Heading Angle (deg.)</th>
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</table>

Table 1. Flight testing parameters

VI. Conclusion

This paper has outlined the benefits, current understanding, and challenges of creating a flapping wing micro air vehicle. Also, the advantages over fixed-wing and rotary-wing models in the areas of flight maneuverability, agility, and stealth were discussed. The aim of the research is to evaluate the effect of gust on the flight performance of a flapping wing MAV. A prototype vehicle is currently being constructed using a rapid prototyping machine and a DC motor-gear system. In order to test the MAV at different pitch and heading angles, a mounting support system was manufactured to allow a \( \pm25^\circ \) range of angle change. Experiments will be conducted using the preliminary flight testing parameters in Table 1, and results will be discussed at the conference. The overall goal is to quantify the performance of flapping wing flight as a function of various gust speeds and to aid in the design and evaluation of future models.

Acknowledgments

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References


